ADVANCED ELECTRIC MOTOR
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ADVANCED ELECTRIC MOTOR TECHNOLOGY FLUX MAPPING 5-32903

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16. ABSTRACT

Building upon work performed under NAS8-36955, D.O. 121, in which EMA requirements were generated and electric motor requirements generated; this work progresses to design and investigate permanent magnet motor realizationss for the EMA application.

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ABSTRACT

This report covers the design of electric motors which fulfill the needs of Thrust Vector Control (TVC) actuators used in large rocket propelled launch vehicles. To accomplish this end the methodology of design is laid out in some detail. In addition a point design of a motor to fulfill the requirements of a certain actuator specified by MSFC is accomplished and reported upon. In the course of this design great stress has been placed on ridding the actuator of internally generated heat. To conduct the heat out of the motor use is made of the unique properties of the in house MSFC designed driving electronics. This property is that as long as they are operated in a quasi-linear mode the electronics nullify the effects of armature inductance as far as the phase of the armature current versus the rotor position is concerned. Actually the additional inductance due to the extended end turns in this design is of benefit because in the shorted armature failure mode the armature current in the fault (caused by the rotor flux sweeping past the armature) is diminished at a given rotor speed when compared to a more conventional motor with lower inductance. The magnetic circuit is analyzed using electromagnetic finite element methods.

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The authors gratefully acknowledge the stimulating discussions they have had with Messrs, Cornelius, Harbison, Myers, Cowan and the technical coordinator Ms. Rae Ann Weir. The data and information obtained have assured a design which can be integrated in the MSFC actuator design in such a way as to maximize the heat flow from the electric motors into the actuator.

PREFACE

This technical report was prepared by the Space Systems and Technology Laboratory (SSTL) of the University of Alabama in Huntsville Research Institute. This is the final report of work performed under contract NAS8-38609, Delivery Order 36.

The principal investigator was Dr. George B. Doane III, coordinator of the SSTL. Much of the technical work was contributed by Dr. Warren Campbell and Mr. Garvin Dean.

Ms. Rae Ann Weir of the Control Mechanisms Branch, Component Development Division, Propulsion Laboratory, MSFC/NASA was the technical coordinator for MSFC.

The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official; MSFC position, policy or finding unless so specified by other MSFC/NASA documentation.

Except as may be otherwise authorized this report and its findings require MSFC approval before release to third parties.

George B. Doane III, Ph.D., P.E.
Principal Investigator

Approval:
Research Institute

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STATEMENT OF RESEARCH PROBLEM AREA

The specific task undertaken concerned itself with the design of electric motors for use with electromechanical actuators (EMA) used for thrust vector control. The outcome of the task was to provide insight into the design of motors in general, to provide insight into and solutions to problems unique to this EMA application and to provide a point design for an in-house MSFC EMA design.

It was stipulated that brushless DC motors were the baseline technology. The motors were to be driven by MSFC designed electronics (a fortuitous choice as it turned out).

The physical envelope into which the motors were to fit was determined by an existing MSFC actuator design. As it turned out this forced several features of the design. See discussion of results.

ANALYTICAL BACKGROUND

All the phenomena of electromagnetic may be traced to Maxwell's equations. Until recently their direct use in low frequency analysis situations was limited because of the difficulty of solving them to obtain engineering results. This situation has changed somewhat with the advent of finite element approaches and the companion use of the computing power which has become available(1).

Maxwell's equations are listed below for convenience (2).

$$\nabla \times \underline{H} = \underline{i} + \frac{\partial \underline{D}}{\partial t}$$

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

Where $\underline{H}$ is the magnetic intensity, $\underline{E}$ the electric vector, $\underline{B}$ magnetic flux density, $\underline{D}$ the electric flux density and $\underline{i}$ the conduction current. The term

$$\frac{\partial \underline{D}}{\partial t}$$

is the displacement current and at low frequencies such as are encountered in motor work may be assumed to be negligible (zero).

In as much as the magnetic field is globally solenoidal (sourceless) the divergence of $\underline{B}$ is zero and it is valuable as well as possible to find a magnetic potential vector, $\underline{A}$. This is done by noting that $\underline{B}$ is a vector and thus may be considered to be the curl of another vector $(\underline{A})$(2).

$$\underline{B} = \nabla X \underline{A}$$

This development is particularly relevant to this work because the finite element program ANSYS produces $\underline{A}$ values as part of its operation. $\underline{A}$ may in turn be used to evaluate the back emf in the motor at any given speed. This development is as follows. From Faraday's Law

$$\mathrm{EMF} = -\frac{\partial \Phi}{\partial t}$$

where the flux is given by (for a given surface)

$$\Phi = \int \underline{B} \cdot d\underline{a}$$

and the voltage between two points is given by the line integral

$$V_{1,2} = \int_1^2 \underline{E} \cdot d\underline{s}$$

Substitution yields

$$\int_1^2 \underline{E} \cdot d\underline{s} = -\frac{\partial \Phi}{\partial t} = -\int \frac{\partial \underline{B}}{\partial t} \cdot d\underline{a} \cdot$$

Applying Stokes' Theorem from vector analysis converts the line integral on the left to a surface integral.

$$\int (\nabla \times \underline{E}) \cdot d\underline{a} = -\int \frac{\partial \underline{B}}{\partial t} \cdot d\underline{a}$$

From this it is seen that

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

Making use of the magnetic potential formulation ($\underline{B} = \nabla x \underline{A}$) then

$$\underline{\nabla} \times \underline{E} = -\frac{\partial(\nabla \times \underline{A})}{\partial t}$$

So that

$$\underline{E} = -\frac{\partial \underline{A}}{\partial t}$$

In this work interest is in voltage induced along one side of a coil of wire placed in the motor stator slots. This defines the directions of interest. Letting $\underline{A}$ be directed along one side of the coil (down the slot) the electric vector $\underline{E}$ may be calculated provided the speed of the motor vector is specified (i.e. to make a numerical approximation to Δt) and $\Delta \underline{A}$ is found from A in the wire or coil side for different angles between the stator and the rotor magnets. Multiplying $|\underline{E}|$ by the length of the axially directed coil side yields the voltage of one coil side. Thus the voltage around the coil is given by

$$V = 2|E|\ell n$$

where n is the number of turns in the coil, ℓ is the length of a coil side in a slot and the 2 accounts for the coil having two sides in which voltage is being induced. This approach is different from the more familiar expression

$$e = b\ell v^{(3)}$$

where v is the relative velocity of the flux density B and the length ℓ. This is a simplified expression in that B and ℓ are assumed orthogonal, the more correct expression is

$$e = (\underline{B} \cdot \underline{v})\ell^{(3)}$$

This latter formulation is sufficiently removed from the first enumerated approach using $\underline{A}$ to be used as a "sanity check" on the results of the approach using $\underline{A}$ (which should be more accurate if $\underline{B}$ is estimated from an ANSYS flux plot).

Likewise there is a dual approach to calculating the torque developed by an electric motor. The more accurate one used by ANSYS is to evaluate the torque by means of the Maxwell stress tensor. (4) (5) The form of it useful here is

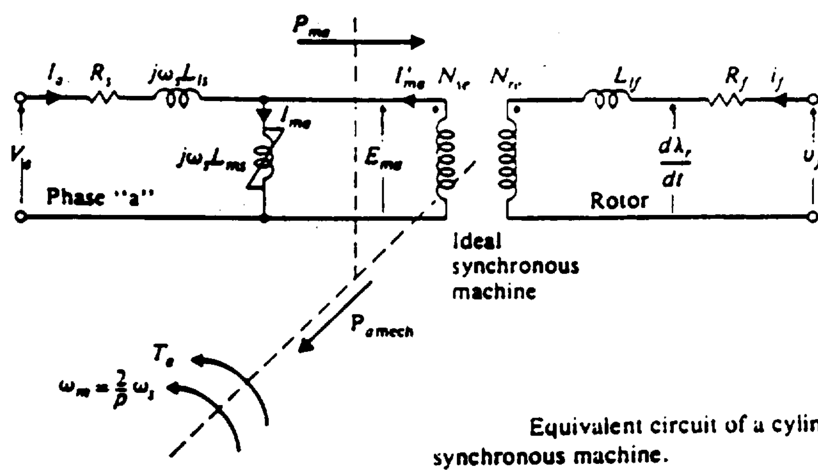
$$\underline{T} = \int [(\underline{B} \cdot \underline{n})\left(\frac{\underline{r} x \underline{B}}{\mu o}\right) ds$$

This formulation is the one leading to the conceptual device of visualizing elastic strings (rubber bands) with one end attached to the stator and the other to the rotor so that as the stator associated mmf moves it tends to drag the rotor with it. Put a little more formally the magnetic field is attributed to posses stress analogous to stress in a structural member and in each case is associated a force on the surrounding environment. Similar to the voltage calculation there is a better known way in which to calculate force on a conductor and hence torque on a rotor. It is to use the formula (3)

$$T = rF = Bilr$$

where T, F, B and i (or l, in which i flows) are all orthogonal. In using this formula it is assumed that the current conductors which are really in the slots, are uniformly distributed around the stator side of the air gap. As Liwschtz-Garik has noted experiment confirms the legitimacy of this procedure(17).

Although the type of motor under consideration is sometimes called a brushless dc motor (because of the obvious lack of brushes and the fact that its power source can ultimately be traced to a dc bus) it is in reality more properly thought of as a synchronous motor. There are two major differences between this motor and the classical synchronous motor. One difference is that the electrical supply is controllable both as to current magnitude and phase (relative to the rotor-stator instantaneous geometry) and its temporal frequency (and hence the synchronous speed of rotation). The other is that the flux due to the rotor comes from permanent magnets rather than from electromagnets. Any course about electrical machines develops the equivalent circuit of the synchronous machine. References are numerous, see for instance numbers six and seven. This is done on a per phrase basis under the assumption of balanced three phase excitation and operation. Reference 6 develops one as shown below.

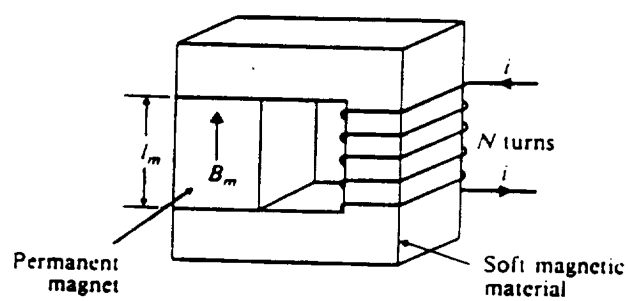


Equivalent circuit of a cylindrical-rotor synchronous machine.

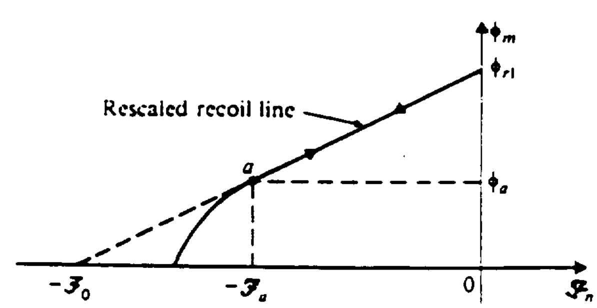
This equivalent circuit is of one phase, the a phase, and hence the various a subscripts. Lms is the usual magnetizing inductance (with the reactive VARS drawn from the a source) here shown nonlinear, Ws is the synchronous speed (rad/sec), Wm is the mechanical speed of the rotor, Ta the torque assigned to the a phase, Rs and Ls the stator resistance and inductance, Nse and Nre the stator and rotor effective number of turns and Ia and Va the a phase amps and volts. The rotor is characterized by the field resistance (Rf) and inductance (Lef) and coupled to the stator through the ideal transformer as shown.

Reference six, through a series of transformations particularizes this general equivalent circuit to that corresponding to a cylindrical permanent magnet rotor design. It is insightful to point out some interesting steps in evolving permanent magnet equivalent circuits. This development parallels that in reference six to where the interested reader is directed for a more detailed account.

Consider the permanent magnet - soft iron circuit shown below in which the mmf required to established flux in the soft iron is assumed to be negligible.



The permanent magnet has a cross section of area Am and length lm. The next figure shows the relationship between the magnetic flux Øm and the mmf Ѕn due to the current i in the N turns.



This graphical relationship between flux and mmf is obtained by rescaling a B-H curve normally furnished by the material supplier to the dimensions of the specified magnetic circuit. It should be noted that point a is where the demagnetization curve and the recoil line part company and that if the material is driven to the left of point a permanent weakening of the magnet will occur. It should also be noted that as the temperature of the magnet rises such a point will shift to the right. Thus as the magnet temperature rises it becomes progressively easier to weaken the magnet. It has been reported that such behavior may already have been observed in some designs. For this reason the designs done herein intentionally oversize the magnet (compared to using the maximum energy design points usually recommended).

It will be appreciated in the model that a perfect transformer is being modeled in that there is no leakage accounted for. In order to obtain a linear model operation must be restrained only to the linear recoil line. The flux present in the core is found on the straight line which may be expressed as

$$\varnothing m = \Im m /_{Ro} + \varnothing rl$$

$$\text{where } \frac{\varnothing r\ell}{\Im e} = \frac{1}{Re}$$

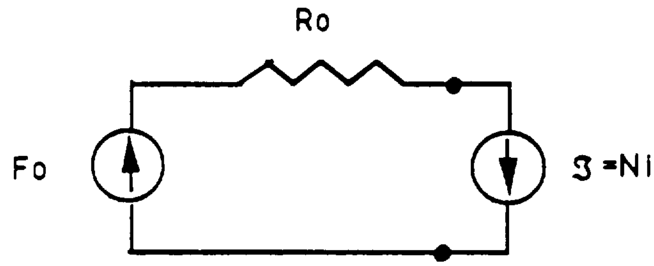
this may be manipulated to

$$Ro\varnothing m = \Im m + Ro\varnothing r\ell$$

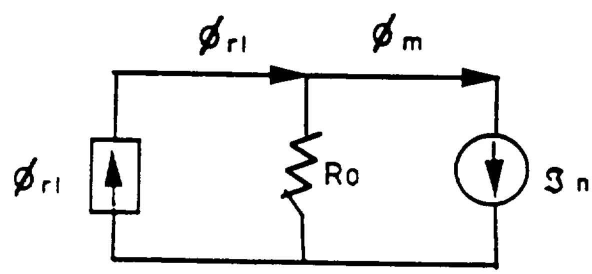
or

$$Ro\varnothing m = \Im m + \Im o$$

From this follows the equivalent circuit



Applying a Thevinen equivalent to the circuit to the left of the terminals yields



This in turn may be converted into an equivalent electric circuit as follows

$$i = \frac{\Im}{N}$$

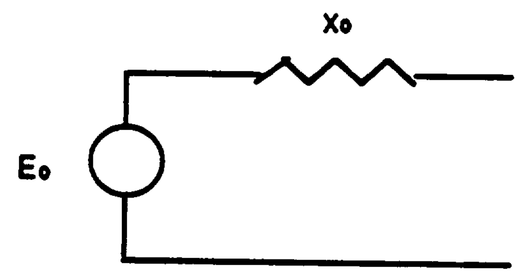
$$e = N\frac{d\Phi}{dt}$$

$$\Im = R\Phi$$

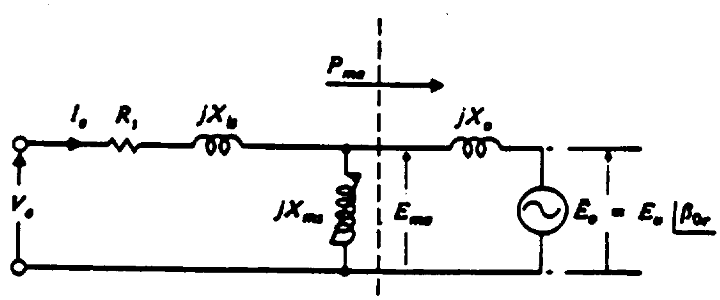
Substituting

$$V = N\frac{d}{dt}\left[\frac{\Im}{R}\right] = \frac{N}{R}\frac{d\Im}{dt} = \frac{N^2}{R}\frac{di}{dt} \triangleq L\frac{di}{dt}$$

Thus an equivalent circuit of the form



emerges. This may then be substituted for the rotor circuit of the original equivalent circuit to yield a per phase steady state equivalent circuit as



The relevance and importance of the foregoing is that there is firm ground to think of a multiphase motor on a per phase basis provided it is being operated in a balanced fashion. This fact is used in sizing the motor.

MOTOR DESIGN CONSIDERATIONS

Initially it was thought that a 5 inch diameter motor would be allowable. Subsequently it was decided that 3 inch diameter motors would be needed to fit a four electric motor actuator that MSFC has designed in house. From those exercises it seems that the somewhat larger diameter motor would be preferable because it allows keeping the speed at rated power and the length to diameter ratio smaller than is the case with the smaller diameter motor.

The specification called for the actuator to develop 30 horsepower under nominal conditions but be able to develop 45 horsepower peak under off nominal conditions. Probably a desire to develop 30 horsepower at a stroking velocity of 5 inches/second and a stall force of 60,000 pounds gave rise to these specifications (30 horsepower at 5 in/sec requires 40,000 pounds of force). Thus designing each motor for 7.5 horsepower nominal with a surge possibility of 11 horsepower seems to be reasonable. The gear train connecting the motor to the load is two pass. One pass is a spur gear ratio in the range from 1 to 10. The other pass is roller screw gear with a range up to 1 inch per revolution possibility. Previous work [4] has shown the desirability of matching the reflected inertia of the load to that of the motor to the extent possible while still meeting the stall force requirement.

When assigning a power rating to an electric motor close attention needs to be paid to the methodology followed. Electrtic motors are basically power limited by heating. Heating of the insulation of the wire used in the coils and, in a permanent magnet design, by magnet heating are principal questions. Overheating the wire insulation will drastically shorten its life even if not driven to instantaneous failure. The permanent magnets, as already noted, will, even below their Curie temperature, be susceptible to permanent irrevocable weakening because of the shift with temperature of the point where the demagnetization curve and the recoil line diverge.

Thus various ways of stating power ratings are encountered (sometimes for the same machine). Terms such as continuous rating, peak rating, time limited rating (all these with side conditions on the ambient environment, duty cycle, type of housing etc.) are found. They are codified for industrial use in the NEMA (national electrical manufacturers association) standards. The question here is how to rate the motors used in electromechanical actuators (EMA) used for large launch vehicle thrust vector control (TVC).

Inspection of the flight records of Shuttle flights discloses very little activity of the actuators. The identifiable active times are during the initial roll maneuver to obtain orbital azimuth and during the maximum dynamic pressure encounter (max Q) when the air loads on this asymmetrical vehicle peak. But none of these loading periods last very long. Indeed the whole powered booster flight is about two minutes (without on average much activity). Thus short of an unspecified anomaly something other than flight stress needs to be used. Experience has shown many times that test and checkout of equipment stresses it more than flight. Operation in a boatail of a stacked vehicle at KSC in August during a functional checkout might be a high temperature regime. Perhaps others exist also. The current hydraulic actuator specifications [8] call for "operating performance...during and after exposure to..." an ambient of -40 to +275°F (-40°C to + 135°C). The low temperature end of the scale would seem to impinge on electronic and mechanical things rather than electromagnetic concerns. The upper temperature range, when one considers that it begins to approach the upper limit of allowable magnet temperature is a problem. The magnets are innermost in the motor material and while heating of the rotor will be minimized by every means (e.g. using a laminated rotor) still heat generated there must cause a sensibly higher temperature than the ambient in order to make its way out through the air gap (radiation, perhaps convection) and the shaft (through the bearings). MSFC (Mr. Martin, EP-64) has

indicated upon questioning that the upper temperature might be modified as it is derived from a standard aerospace specification. To grasp the problem more quantitatively an estimate of the heat transfer possible from the body of the actuator was made as detailed in Appendix A. This development assumed that the motor heat is to be dissipated from the aft body or tailstock end of the actuator and that the actuator may be approximated by an equivalent right circular cylinder. For worst case conditions it was also assumed that the cylinder was horizontal. The natural convection heat transfer coefficient was obtained from reference nine. The results of the analysis are presented in Appendix A as the figure on page 37. They show that heat dissipation during a stalled or otherwise loaded condition (i.e. high current) will be a problem. It may be ameliorated by the use of fins, perhaps a brake with the motor unenergized during motionless periods (adds complexity) or in extremum use of cooling air from a fan or other source. Once again the necessity of providing a low thermal resistance path from the origin of the heat to the actuator body is made plain. Appendix B does show for a representative geometry that if the thermal conductivity of the end turn to copper heat sink can be made approximately comparable to that of one inch of the wire itself than long periods of stalled operation could be thermally tolerated.

In appendix C the core loss analysis is detailed. It shows that even under worst case conditions the temperature rise in the stator iron is small (delta temperature of 10-11°F above stator outer temperature). Thus this factor is not a serious temperature rise concern. Comparing the wire temperature analysis to this one shows clearly that if a way could be found to couple the wire thermally to the stator iron an appreciable amount of heat could be extracted from the wire (recall that in appendix B it was assumed that all the heat exited the copper wire via the end windings). This might be brought about if the wires could be potted into the slots with something like the Stycast material. This latter might present fabrication problems and would have to be investigated.

The lamination design was driven by two factors. One was the fixed outer diameter (OD) of three inches. The other was the choice of the number of poles. The choice of the number of poles for a synchronous motor intended for conventional service is straight forward. For a three phrase p-pole, synchronous machine the relationship between mechanical shaft speed and the angular frequency of the supply is

$$wm = \frac{2}{p} ws \qquad \text{rad/sec.}$$

Thus if the supply is 60HZ the only useful speeds i.e. those at which mechanical power can be produced[6] are the discrete values 3600 rpm, 1800 rpm, 1200 rpm etc. Therefore to choose the number of poles the load speed characteristic is considered and a straight forward choice made. No such situation obtains here. In effect the electronics powering the motor can (and do) produce a wide range of frequencies. Thus some other criterion was needed. The initial choice made was to optimize the various possibilities according to the maximum torque they produce when full pitched windings are used. As seen below this led to an initial choice of a 4 pole design. To do this a series of 3 inch OD laminations were designed according to the procedure outlined below. They were then modeled in ANSYS and torque versus torque angle data gathered. Laminations incorporating 8, 6, 4 and 2 poles were designed and so evaluated. As is seen in the table below the torque production peaked for the 4 pole machine. However when later the zero current or reluctance torques were evaluated the choice changed to that of the 6 pole motor.

Number of		3" Torque		5" Torque	
Poles	Slots	Max.	No Current	Max.	No Current
2	3x2x3 24	78	27.3	—	—
4	3x4x2 24	108	26.4136	—	—
6	3x6x2 36	96	0.79968	163.722	-1.89312
8	3x8x2 48	77	-4.68328	—	—

The units of torque are Newton-Meters per meter length of the rotor.

All the laminations were designed basically the same way. With the OD specified a priori the consensus formulas from reference fifteen (section 9-73) were used. But first it was necessary to decide how many slots would be specified for each number of poles. Also rationale pro or con fractional slotting was considered. Fractional slotting is often used when a lamination design exists and it is desired to use these laminations for a new design for which they were not designed. Other reasons to use fractional pitch windings include noise, wave form and locking torques specially on machines of eight or more poles[15]. This is because it behaves as a winding with many slots per pole per phase which reduces the distribution factors of the harmonics. Clearly if the number of slots per pole per phase became less than two a fractional slot design would be called for because a single slot per pole per phase will in all likelihood lead to large harmonics[16]. Induction or synchronous motors have essentially the same stator laminations and are designed in most cases with integral slots. Here there are less than eight poles and more than one slot per pole per phase. Therefore integral slots were chosen as appropriate and consistant with the general motor design literature. This choice renders the machine electrically easy to balance, makes analysis simpler because only one pole of the machine need be modeled (with appropriate boundary conditions) whereas a non integral machine must have the full 360 mechanical degrees modeled. However if testing shows the desirability of non integral slots and fractional pitch windings they could be designed. Two samples of commercial motors examined do indeed have non integral slot designs. The consensus formulas (dimensions in inches) are (given OD)

$$\text{inside diameter of rotor, } D = \frac{OD - 0.647}{1.175 + (1.03/P)}$$

where P is the number of poles.

The diameter of the bottom of the slots is

$$D_1 = 1.175D + 0.647$$

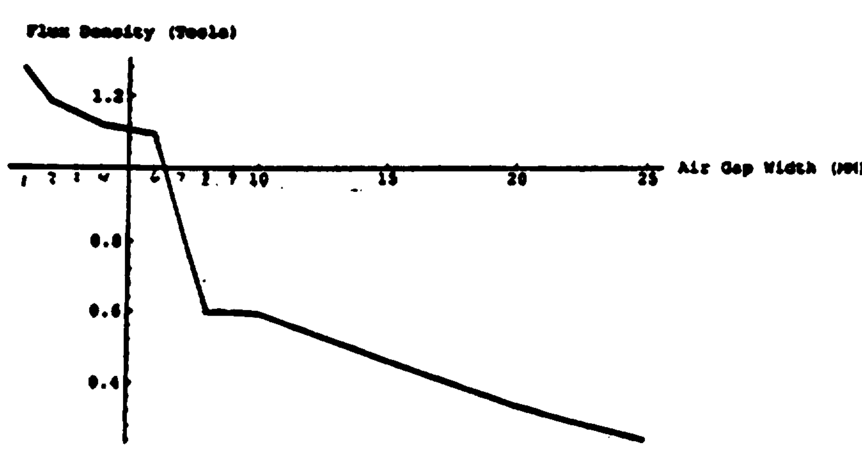
and the tooth width

$$tw = \frac{1.35D}{S_1}$$

where S_1 is the number of slots. For partially closed slots the pole tip to pole tip distance e^1 is given by

$$e^1 = 0.0143D + 0.0643$$

The value resulting from these formulas are likely dimensions for trial designs. However they have proven to be good guides. During the course of this design effort the outer radius of the motor (i.e. the OD) was increased as a trial. The torque analysis showed that even at high flux levels little torque gain resulted although of course the back iron flux density decreased. A value of one millimeter (about 4 mils) was chosen as the air gap between rotor and stator. This may be a little too small when the mechanical design is executed. A study was done which showed the air gap flux density to be a weak function of the air radial gap as long as that gap is small compared to the air gap between the alternating magnet edges. In the figure below the distance between the magnets was approximately 7 mm.



It is seen that another one or two millimeters would not be too bad although the gap should be kept as small as possible to achieve maximum air gap flux density.

As previously discussed it was decided to have an integral number of slots per pole per phase. Thus for the six pole machine use of the pole /slot formula

No. of slots = No. of phases X No. of poles X No. of slots per pole per phase

or here yields the number of slots as

$$36 = 3 \times 6 \times 2$$

Applying the consensus formulas yields

$$D = 1.7473$$

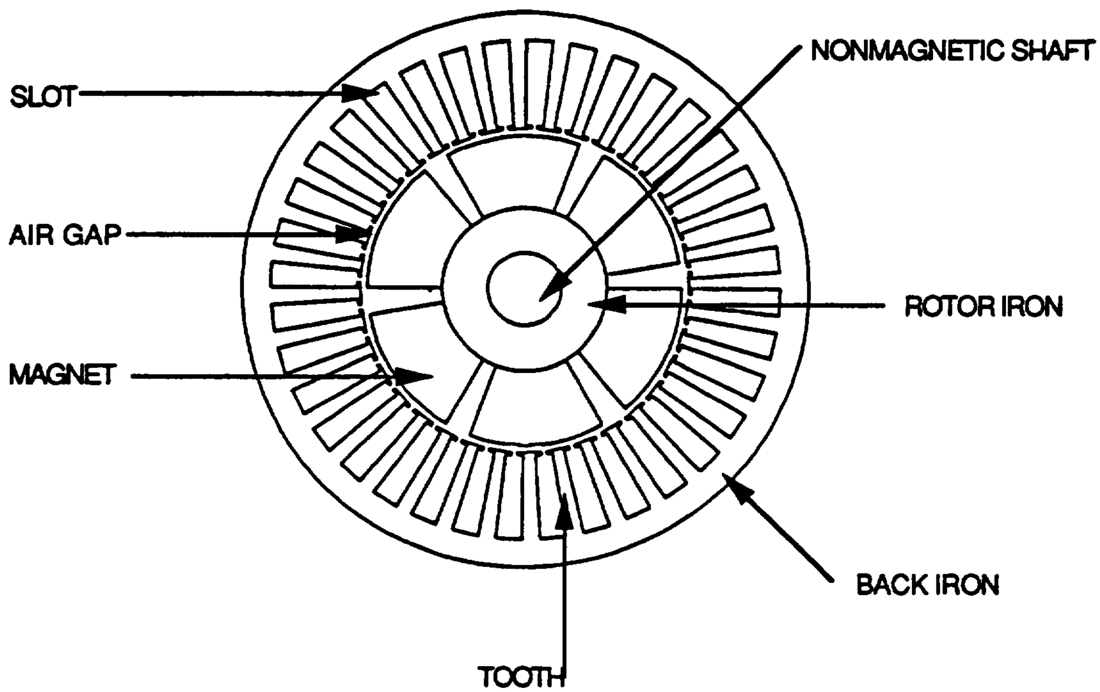
$$D_1 = 2.7000$$

$$tw = 0.0655$$

$$e^1 = 0.0893$$

It will be seen from the lamination figure that these values were adhered to by and large.

LAYOUT OF A 6 POLE 3" OD MOTOR



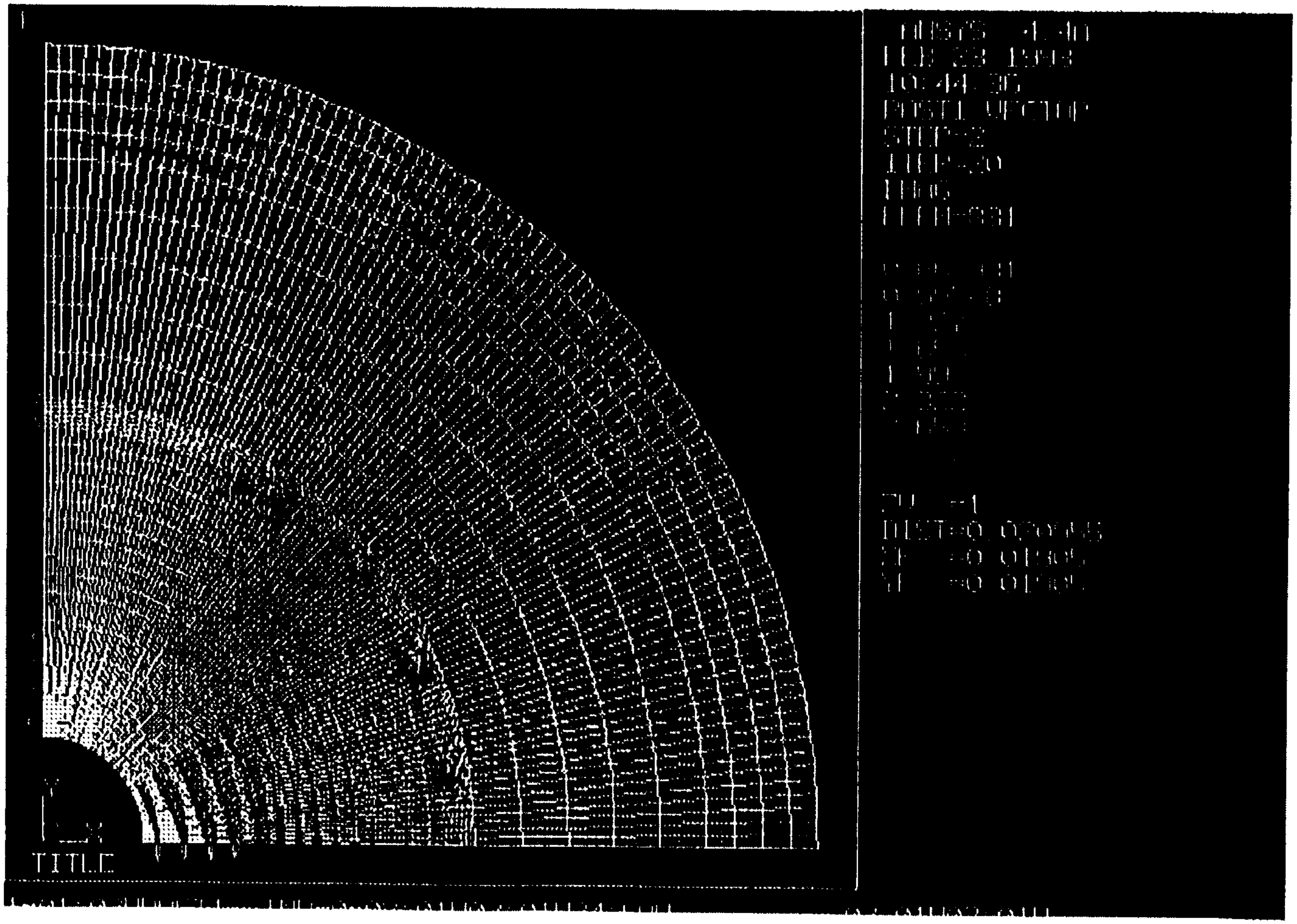
This same procedure was followed for 2, 4 and 8 pole designs. This was required to model them in ANSYS for the torque, flux and back EMF evaluations.

As previously mentioned when discussing torque optimization all the work so far has been done with full pitch windings. However it may be desirable to chord or short pitch the stator windings to minimize harmonics. With two slots per pole per phase it would be possible to short pitch the winding by 30 electrical degrees (one pole is 180 electrical degrees, thus 180 divided by 6 yields 30 electrical degrees per slot). A 150° pitch yields pitch, distribution and combined factors for various harmonics as [7]

Harmonic	Pitch (150°=5/6)	Distribution Factor	KpKd
Fundamental	0.966	0.966	0.933
Third	0.707	0.707	0.499
Fifth	0.259	0.259	0.067
Seventh	-0.259	0.259	0.067
Ninth	-0.707	0.707	0.499
Eleventh	-0.966	0.966	0.933

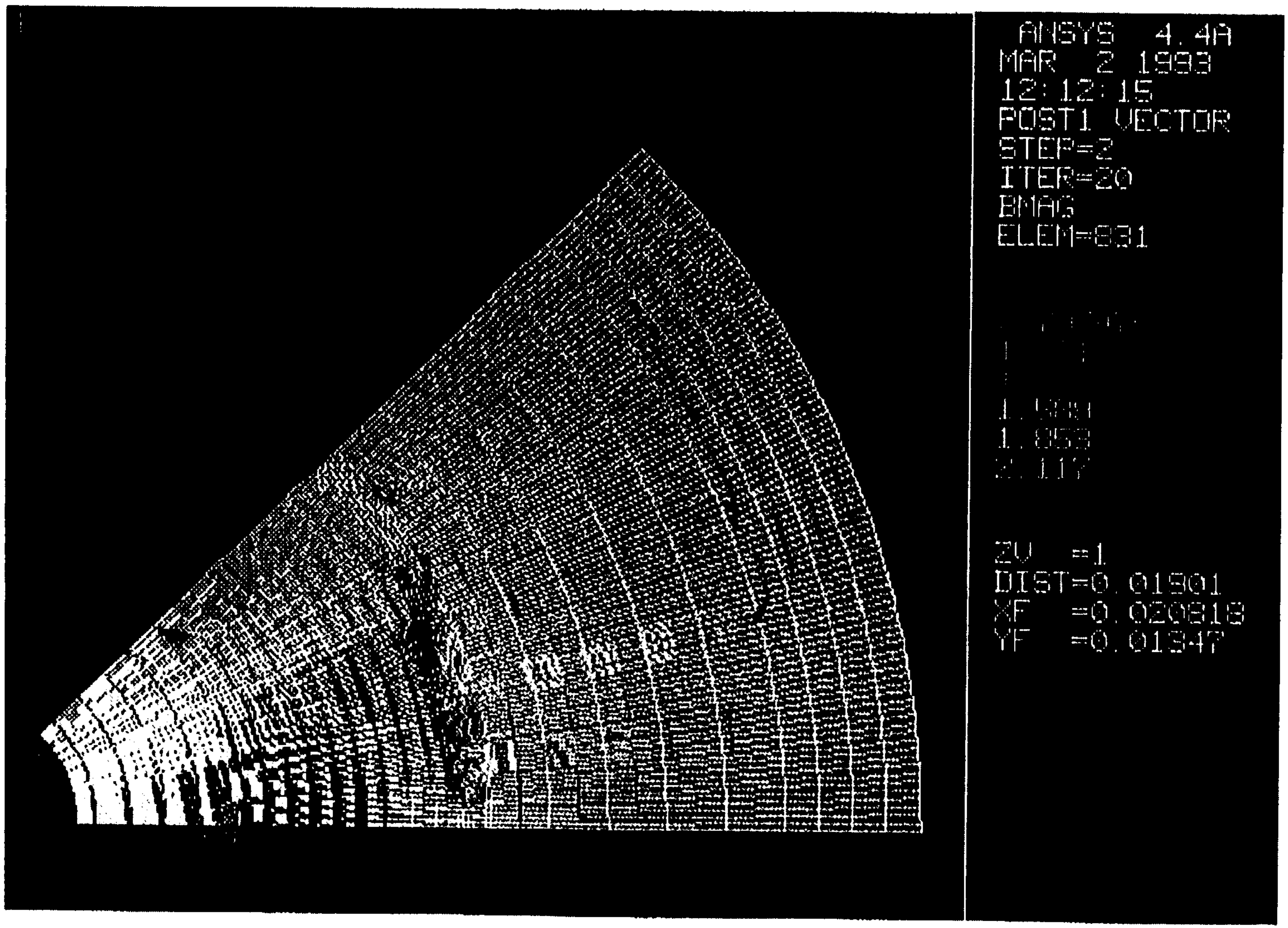
From the table it is seen that the desired fundamental is diminished only 6.7% where as the other harmonics are diminished quite a bit. Connecting the motor in wye or star will eliminate the third harmonic at the terminals and as a delta connection would allow circulating third harmonic currents, a wye connection is chosen. The details of the winding are given in appendix D. The flux plot, see p. 21, of the 4 pole design is interesting. As previously pointed out only one quadrant of a 4 pole motor needs to be modeled (360°/4=90°). The flux densities are shown in various colors ranging from dark blue to red. The peak air gap flux is quite high (above 2.9 Tesla) and perhaps just as

4 Pole 3" Motor

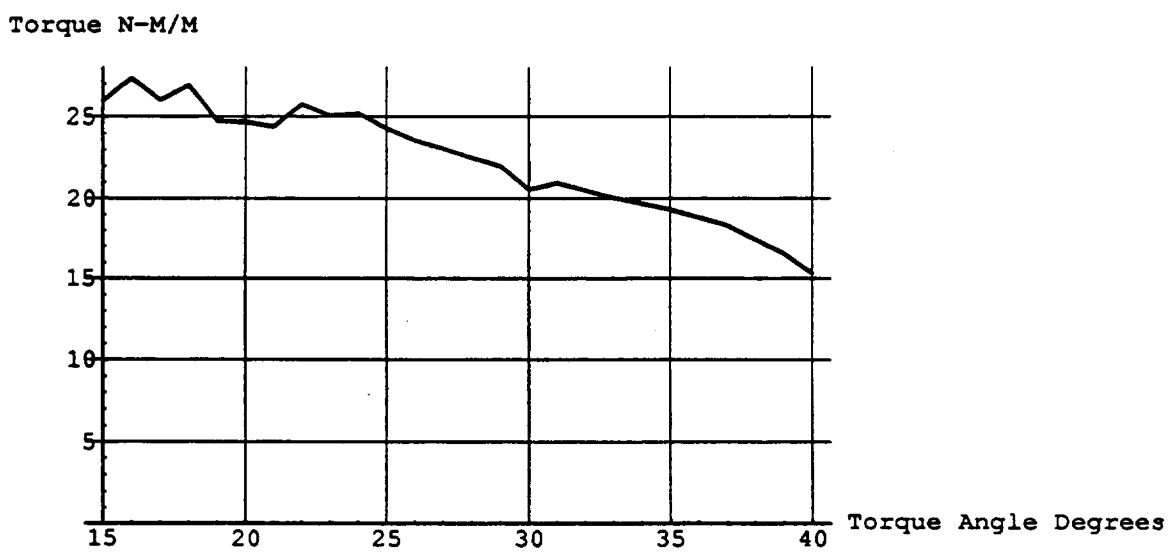


important is oriented rather close to the optimum angle of 45° as derivable from the Maxwell stress expression based torque equation [4]. Both of these factors explain the high peak torque production. At this point it is instructive to compare the flux plot of the 8 pole machine to that of the 4 pole machine. The plot is given on p. 23. Note that the overall levels of flux density are lower than for the 4 pole case. Also notice that there is only one area of 2.38 Tesla flux density per pole here whereas there were four areas of nearly 3 Teslas flux density per pole in the 4 pole case. Also notice that while much of the flux density orientation in the four pole case approximated the optimum 45 degree angle little of the flux (at a lower density level) in the eight pole case favored the 45 degree optimum. This spreading of the flux amongst a number of teeth may explain why the reluctance torque of the 8 pole motor is so low. The next figure, on p. 24, is a plot of torque (in Newton-Meter/Meter of motor length). From this it is seen that torque remains within approximately 2 N-M/M of the maximum for commutation angles of 20° of peak. Thus it is seen that to minimize torque ripple and retain a maximum torque capability at all shaft positions the use of a revolver based rotor - stator position sensor is desired rather than the 6 segment 3 Hall effect 60 electrical degree switching sometimes used.

Stress Plot of an 8 Pole 3" Motor



```
In[37]:=
  T4 = {{15,25.952},{16,27.347},{17,25.992},{18,26.906},
  {19,24.727},{20,24.685},{21,24.417},{22,25.725},
  {23,25.065},{24,25.183},{25,24.337},{26,23.6},
  {27,23.091},{28,22.5},{29,21.984},{30,20.555},
  {31,20.973},{33,20.02},{35,19.303},{37,18.303},
  {39,16.548},{40,15.31}}
  ListPlot[T4,PlotJoined->True,GridLines->Automatic,
   AxesLabel-> {"Torque Angle Degrees",
  "Torque N-M/M"},PlotRange->{0,28} ]
```



Knowing that a full slot of 8 MA/M^2 current density produces about 96 N-M/M of torque the motor sizing may be completed. For the ensuing calculations a fill factor of 50% will be assumed which means the peak torque actually available will be 96/2=48 N-M/M. The problem now is to establish the length of the active rotor and the speed at which rated power is to be developed. To keep the rotor length as short as possible the highest rotation speed thought practical i.e. 20,000 rpm was chosen. The rotor length calculation, assuming 48 N-M/M of torque is available to produce 7.5 horsepower is a follows.

$$48\frac{\mathrm{N-M}}{\mathrm{M}} \times 0.7376 = 35.4\frac{\mathrm{lb-ft}}{\mathrm{m}}$$

$$7.5\mathrm{horsepower} \times 550\frac{\mathrm{lb-ft}}{\mathrm{sec \cdot HP}} = 4125\frac{\mathrm{lb-ft}}{\mathrm{sec}}$$

$$20{,}000\ \mathrm{rpm} = 2094\ \mathrm{rad/sec}$$

$$2094\frac{\mathrm{r}}{\mathrm{sec}} \times 35.4\left(\frac{\mathrm{lb-ft}}{\mathrm{m}}\right) \times \ell(\mathrm{m}) = 4125\left(\frac{\mathrm{lb-ft}}{\mathrm{sec}}\right)$$

$$\ell = \frac{4125}{(35.4)(2094)} = 0.05565\mathrm{meter}$$

or

$$\ell = (0..05565)(39.37) = 2.191\mathrm{inches}$$

The rotor force stress is calculated as follows. The equivalent maximum tangential force is

$$(\mathrm{F} \cdot \mathrm{r})(\mathrm{Speed}) = \mathrm{power}$$

$$\mathrm{F} = \frac{\mathrm{power}}{(\mathrm{radius})(\mathrm{speed})} = \frac{4125}{\left(\frac{1.75}{2(12)}\right)(2094)}$$

$$F=27.02 \text{ lbs}$$

The rotor surface area is

$$\text{Area} = (1.75\pi)\,(2.2) = 12.1\text{in}^2$$

so the force density is

$$\delta = \frac{F}{A} = \frac{27.02}{12.1} = 2.233\frac{\text{lb}}{\text{in}^2}$$

This is in line with usual good industrial practice(17). See discussion in Appendix I.

As was noted earlier a late switch was made in the choice of 6 versus 4 poles. Evaluating the A values requires many ANSYS runs and hence was not repeated. The method remains the same for any number of poles. To determine the number of turns per coil per pole ANSYS was queried to produce the magnetic potential (4) at the various coil locations so that the procedure described early in this report could be applied. The value of A at each side of each coil location or slot was found for a variety of rotor - stator angles and then averaged. These data were entered into a spread sheet program to find the coil (one turn) induced voltage. The spread sheet results are displayed in Appendix E. These results were calculated assuming a 10,000 rpm rotor speed 4 poles and a 7 inch long rotor. Because the calculations are linear they may be rescaled to the 20,000 rpm rotor speed as (taking 9V per coil as the spread sheet maximum)

$$9 \times \frac{20{,}000}{10{,}000} \times \frac{7.78}{7} = 20\frac{\text{volts}}{\text{coil}}(\text{max.})$$

In this design where the basic dc bus is 270 volts (which may sag to 240 volts) the terminal voltage value is not critical as long as the back emf of the motor never rises so high as to threaten the linear operation of the current source amplifier feeding the motor. It is estimated that a voltage no higher than 200-210 volts will achieve this. Other than this consideration

there is much more freedom to select maximum back emf i.e. the number of turns in a coil than is the usual case. In this completely balanced electrical design there is freedom to series or parallel the coils in a given phase provided the current rating of any given coil is not exceeded (and since usually all coils are wound with the same wire gage this means having the same current in all the coils). If the terminal voltage is applied to the wye connected motor it is expected that the new phase voltage will be on the order of 200-210 divided by $\sqrt{3}$ (i.e. 115 to 120 volts). At 20 volts per coil only one or two turn coils in series connection (4x20=80 or 4x20x2=160) of all coils would produce an emf less than that desired. If the 4 coils were connected 2 by 2 in series and then in parallel 3 turn coils (3x[20+20]) would yield 120 volts. The third possibility is to parallel all the coils with 6 turns each to yield 120 volts (6X20). Keep in mind that each turn of the coil can be made from wire which in its turn is made from a number of wire strands in parallel. Once again consulting with the winder would help to make the choice by seeing which option will lead to the highest fill factor. It is essential that after a motor rotor and stator have been fabricated and assembled a search coil of a few turns be placed in the stator slots and the actual voltage be measured. With that knowledge the final winding specification can be developed.

In the course of developing the exact winding to be used it should be kept in mind that the mechanical power delivered to the shaft is proportional to the back emf times the current. Thus as the various emf options are considered from the standpoint of winding ease or complexity there are direct implications to the current drawn. That is if the back emf is relatively low then the current drawn has to be relatively high so that their required product i.e. the power delivered) is maintained. Of course the converse is true for a high back emf case.

In a precursor study (reference four) a great deal of effort was spent in studying the interrelationships between the various system inertias. The more or less invariant inertia

component is that of the load (here the reflected rocket motor mass) and the actuator load bearing parts. The variable factors to consider when designing the system include the values of the spur gear ratio and the roller screw ratio between translation and rotation (which among other things has a gear train like inertia reflection property) the pinion and mating gear inertia and the motor rotor inertia. As is shown in the previous final report if the two passes are selected to produce matching of the referred inertias (referred to any common point) then two optimum objectives are achieved. These are first the maximum bandwidth of the actuator (not the motor motion but the output motion) and second the maximum energy transfer to the load. Proper matching does not however generally achieve the other actuator requirement i.e. achieving specified actuator stall force. It was further shown that given a matched situation there is an optimum way in which to "detune" the system so as to achieve the required stall force and yet minimize the loss of system bandwidth and power transfer efficiency. Clearly any energy stored in the motor rotor is not energy getting to the actuator and load combination. Thus minimizing the motor inertia subject to power and thermal considerations is highly desirable. However this must be done in the context of an end to end optimized design to achieve its full potential. Attention is invited to Appendix I as well as the former work's final report for further thoughts on the inertia question.

Conclusions and Recommendations

An extensive array of analytical tools has been assembled to design and analyze electric motors. These have been applied to the point design of a brushless dc electric motor for use with large thrust vector control (TVC) electromechanical actuators (EMA). This array represents the current state of the art in motor design tools. This is exemplified by the use of finite element methods (specifically the ANSYS electromagnetic option 4.4A) to evaluate numerically the motor designs torque characteristics (e.g. torque versus torque angle), the optimum number of poles, the back emf, and to visualize the flux paths of the proposed designs. Use has also been made of a digitally implemented thermal network analyzer that was obtained from COSMIC (and which runs on the PC) to investigate heat transfer in the proposed motor. The designs of almost all electric motors are thermally driven. This design should promote heat removal from the motor to the greatest extent possible. To do this some traditional design principals were contravened with the knowledge that the MSFC electronics will control the current even if the motor inductance is higher than normal.

It will be noted in the table listing torque for various motors and circumstances that a 5 inch diameter motor is indicated. This is because initially such a motor was thought suitable for the actuator. However in addition to the usual tests a number of other tests were made with this model. Basically these tests held the slot current density constant as the motor's slots were elongated. The results of these preliminary tests showed that placing three separate windings in the slots *with the currents in phase* created no particular problem. If the motor were to be powered from a conventional low impedance or voltage source of electrical power it would however be very difficult if not impossible to insure adequately-in-phase currents. This is because as the slots are elongated to accommodate the additional windings the per winding inductance would be markedly different one from another and thus when they are all driven from the same low impedance source the various winding currents would

not be in phase (as is required to produce maximum or additive torque). Furthermore no passive tuning would be able to compensate for this because of the changing frequency applied as motor speed is changed. Fortunately the MSFC amplifier removes this current phasing problem/concern because it incorporates sufficient feedback so that its output current is essentially independent of the load impedance. This latter happy circumstance opens the possibility of incorporating three electrically isolated windings in a single motor stator with one rotor (on a single shaft) with the resulting implications on possible redundancy schemes.

This motor design incorporates an innovative heat dissipation scheme. This scheme makes use of the MSFC amplifier indifference to winding inductance. This indifference allows an increase in the length of the end windings of the motor so as to couple the stator windings thermally with a copper heat sink placed at each end of the motor. The design then is such as to invite the thermal coupling of the motor to the actuator so as to make use of the surface area of the actuator for heat dissipation to the environment.

A design study has also been performed which looks into the use of a Titanium retaining sleeve proposed to be fitted around the rotor magnet structure. The purpose of this sleeve is to assure that the magnets remain tightly fixed to the rotor at high rotor speeds. An ANSYS study of this design disclosed that the Young's Modulus given in the literature for the magnets is extremely low. A check with the manufacturer showed an error of a thousand in the value. The ANSYS program was run with the correct value of Young's Modulus and showed that a feasible heating shrinking scenario is possible for mounting such a ring. An interesting result was that as the diameter of the motor increased the heat shrinking technique became less feasible.

This study has resulted in the electromagnetic design of a motor. There now needs to be a mechanical design made, materials ordered and the design resulting therefrom mechanized. This will serve to explore the ramifications of this outside diameter and thermally driven design. If discrepancies are found between the laboratory results and the analysis they will need to be rationalized.

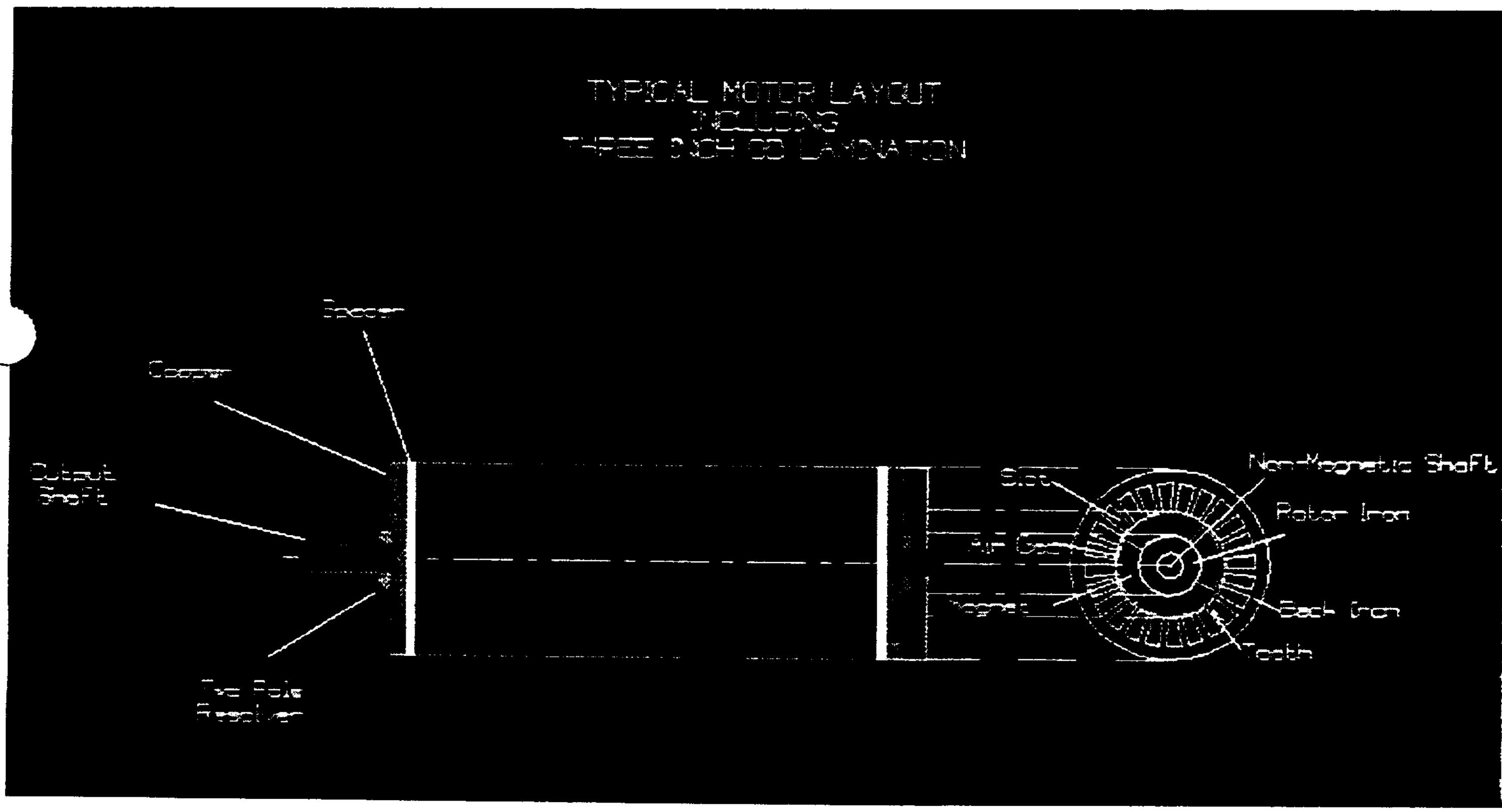
When building the motor the mechanical parts (including the rotor magnets) should be assembled with but a few turn test coil of 6 slot pitch in the stator. The rotor should then be spun at various rpm's to validate the back emf analysis. After this has been done and any modifications to the winding design made the motor would then be wound in the final stator winding configuration. Of course then tests should be performed to determine the developed torque at various electric current levels.

At the conclusion of this build and test cycle there will be a motor design tailored to the TVC application with special emphasis on the heat transfer questions.

In the future if the opportunity should arise to configure a new design it is recommended that serious consideration be given to relaxing the small (here 3 inch) outer diameter constraint. This constraint in the present design has caused the loss of the opportunity to optimize the aspect ratio of the motor. A shorter but larger diameter motor would be worthy of further serious study and would allow the optimization procedure to include additional parameters (i.e. simultaneous inertia matching and stall torque considerations as shown in previous work) than does the present case.

Computer sketches of the motor design are enclosed immediately below.

TYPICAL 2-D MOTOR DRAWING



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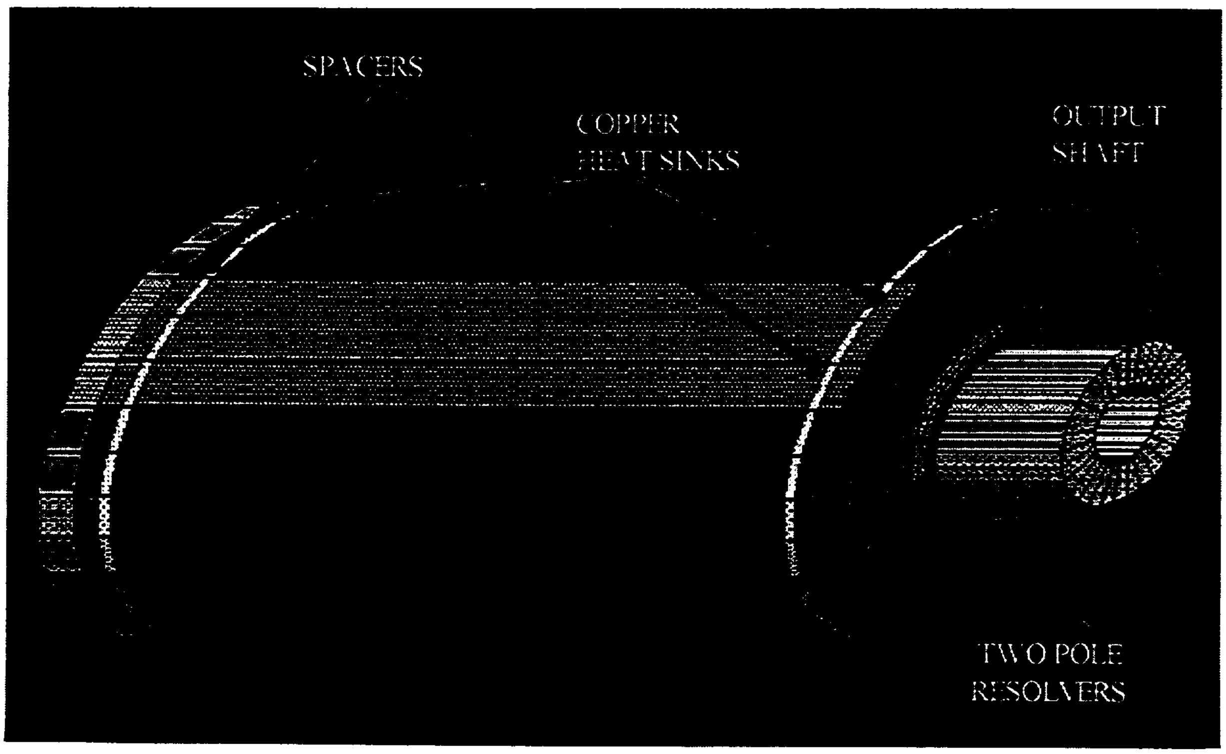
TYPICAL MOTOR 3-D VIEW



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Appendix A:

Heat Loss From Actuator Body

As mentioned in the main body of the text the following calculations were made to gain knowledge of the heat transfer possibilities from the actuator body to the ambient air (at one atmosphere of pressure). Almost certainly test and check out of actuators will take place at one atmosphere. Flight, of course, will rapidly decrease the ambient pressure and heat energy will have to be stored in the thermal capacity of the motor and actuator for the relatively short (less than 10 minutes) flight time.

As previously mentioned the Rockwell Specification document [8] calls for an operating ambient of 275°F (135°C). Magnequench 30 (the permanent magnet material modeled in this study) can withstand 180°C (356°F) to perhaps a maximum of 200°C (392°F). Thus there is something on the order of 80°F to 100°F (26°C to 38°C) between the maximum ambient (275°F) and the magnet temperature. Because most of the heat will be generated in the stator this does not leave much temperature difference to promote the outflow of thermal energy. Clearly if definitive data as to the maximum actual ambient were available (and showed less than 275°F) the situation would be eased.

The actuator body to which the motors are mounted is described in reference 10. For the purpose of this work the tailstock of the actuator was assumed to be the active heat loss part because the bolted flange between it and the headstock end of the actuator is normally a relatively poor heat transmission path.

The heat loss surface was taken to be a right circular cylinder of Aluminum 12 inches in diameter and 14 inches long (based on an estimate of the convecting surface of the housing; in principle fins could be added to aid convection).

Assuming the actuator is small compared to its enclosure and that the enclosure is at the same temperature as the ambient the simplified heat transfer equations may be written as (for radiation and convection).[(9) (11)]

$$qr = \delta\varepsilon_1 A_1\left(T_1^4 - T_2^4\right)$$

$$qc = hc(T_1 - T_2)$$

where

qi = rate of heat flow (BTU/HR)

hc = Convective heat transfer coefficient (BTU/HR-°R)

T_1 = actuator temperature (°R)

T_2 = ambient temperature (°R)

δ = Stefan - Boltzman constant ($0.174X10^{-8}$BTU/FT^2-HR-°R^4)

ε = emissivity of Aluminum

Combining radiation and convection yields.

$$qc + qr = \left\{0.27(T_1 - T_2)^{5/4} + 0.174X10^{-8}X10^{-1}\left[T_1^4 - T_2^4\right]\right\}A_1$$

$$A_1 = 2\Pi r\ell = (2\Pi)\left(\frac{1}{2}\right)\left(\frac{14}{12}\right) = 3.67FT^2$$

$$T_2 = 275 + 459.69 = 734.69^\circ R\_ \text{ (maximum ambient temperature)}$$

The convective heat transfer term uses the relationship from page 177 of reference nine

$$\left[\frac{(T_1 - T_2)}{Do}\right]^{1/4}$$

where

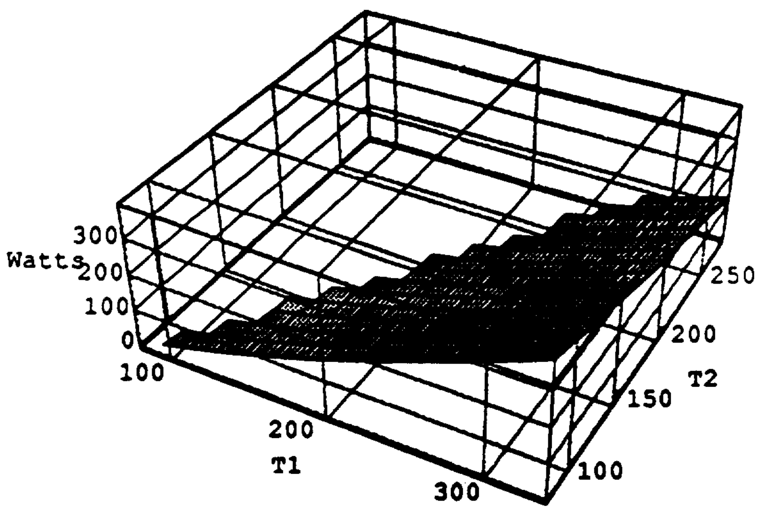
Do = diameter of cylinder (FT)

The emissivity of Aluminum was taken from Table A-23 of reference nine and is representative of a number of Aluminum finishes in the 75-212°F range.

Using the factor 0.293 to convert BTU/HR to watts and plotting the heat transfer for several combinations of T_1 and T_2 (see figure on page 37) it is seen that the housing would have to get fairly warm with respect to the ambient to dispose of appreciable heat. From the figure, if the housing temperature T_1 were at 100°F and the ambient was 75°F the heat loss would be approximately 40 watts and so forth. It is not unusual for one motor of this type to dissipate at least this much power at stall. Here there are four motors; so clearly peak power at stall could be a major problem if the motors are called upon to sustain a large stalled force against a load or are cycled during testing for prolonged periods at high force loading.

In[47]:=

```
aa=0.27 ((t1+459.69)-(t2+459.69))^(5/4)
bb=0.174 10^-9 ((t1+459.69)^4-(t2+459.69)^-4)
Area=3.67
QcQrF=(aa+bb) Area
Plot3D[0.293 QcQrF,{t1,80,340},{t2,75,275},AxesLabel->{"T1"
,T2,"Watts"},FaceGrids->All]
```



Appendix B:

Considerations On Individual Wire Heating

No matter how many or how few turns are called for or how many conductors will be used in parallel ("in hand") for the windings, wire of about AWG25 will be used. This is because of the requirement to fit the wire into the slots and to wind it on a long thin stator. The data in reference twelve indicates current density in the wire as follows.

Standard Machine (Presumably Air Cooled)

$2\ KA/in^2$ to $6\ KA/in^2$

or $3 \times 10^6\ A/m^2$ to $9.3 \times 10^6\ A/m^2$

Exotic Machines (Liquid Cooled)

$12\ KA/in^2$

or $18.6 \times 10^6\ A/m^2$

Pulse Loading

$20\ KA/in^2$

or $31 \times 10^6\ A/in^2$

The maximum current recommended in reference thirteen for 18 AWG (the smallest listed) copper wire according to the National Electric Code is 5 amperes. This yields a current density of

$3.9\ KA/in^2$

or $6.1 \times 10^6\ A/m^2$

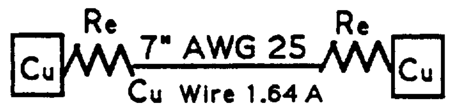
which falls in the standard machine range. There are some exotic wire insulations such as ceramic coatings in existence but it is not clear if they are suitable for use in a motor this size. At 8×10^6 A/m^2 (5.1613 KA/in^2) single 25 AWG wire will carry up to

$$3.173 \times 10^{-4} \times 5161.29 = 1.64 \text{ Amps.}$$

It is common design practice to assume that all the heat energy generated in the stator copper windings should be transported to and dissipated from the end windings. This is generally considered conservative by up to 20% of the heat to be dissipated. The rationale is that the coupling of the wire to the stator iron is nebulous at best (and high resistance) and that conduction through the iron is harder than conduction through the copper. Our laboratory experiment disclosed fairly good iron copper coupling, surprisingly, but no thermal resistance values were obtained (See Appendix G). Dissipating the heat in the end turns commonly leads to having a fan mounted on the shaft of the motor to blow air over the end windings, down the air gap and across the other end winding. This design expedient is not available here. This is a servo motor application i.e. the motor does not spend much time turning and may spend time stalled but producing torque. The design pursued here substitutes large copper heat sinks at both ends of the motor for the usual fan. However, it is still necessary to remove the heat from these copper sinks and to get it into the sinks in the first place.

As a matter of fact approaches reminiscent of this one are found in other servo motors although they are not carried as far as is proposed in this design.

For the sake of preliminary design suppose the wire in the slot is 7 inches long, AWG 25 and that it is carrying 1.64 Amps. In addition suppose it is connected to the two end copper heat sinks by a thermal resistance at each end of the wire (see below).



Assume the Cu heat sinks' temperatures may be varied for analysis purposes. Divide the wire into 7 segments and represent them as lumped conductances of

$$\text{thermal conductance} = \frac{\text{thermal conductivity x cross sectional area}}{\text{length}}$$

$$= \frac{0.061 \dfrac{\text{BTU / SEC}}{\text{Ft°F}} \times \dfrac{2.51 \times 10^{-4}\,\text{Ft}^2}{144}}{(1/12)\text{Ft}}$$

$$\text{Cond} = 1.2795 \times 10^{-6}\ \frac{\text{BTU/SEC}}{°\text{F}} \quad \text{per inch}$$

A transient analysis also requires each node to have a thermal capacity. It is calculated as

Capacity = Volume x Density x Specific heat

Here the

$$\text{Volume} = \left(\frac{17}{12}\right)\left(\frac{2.517\text{x}10^{-4}}{144}\right) = 1.456\text{x}10^{-7}\,\text{Ft}^3$$

so

$$\text{Capacity} = \left(1.456\text{x}10^{-7}\right)(556.42)(0.092) = 7.4564\text{x}10^{-6}\,\frac{\text{BTU}}{{}^\circ\text{F}}$$

The power dissipated in each one inch section of a wire was calculated for the worst case as follows. The resistance of one inch of wire is, at 20°C, given from references 2 and 13 as

$$R_{20}=2.7 \text{ x } 10^{-3} \text{ ohms}$$

This value was adjusted to 180°C by the relationship (13)

$$\text{Rt} = \left(\frac{100}{\text{C}}\right)R_{20}\left[1+0.00393(t-20)\right]$$

where C = percent purity of the copper (used 97%)

t = temperature in degrees Celsius

$$\text{Rt} = 4.5 \text{ x } 10^{-3} \text{ ohms}$$

Thus the power per inch is given by

$$P = RI^2 = \left(4.5\text{x}10^{-3}\right)(1.65)^2 = 0.0123\text{watts}$$

or

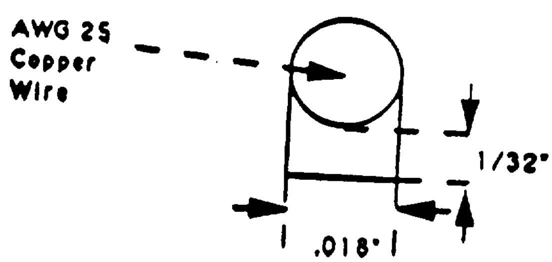
$$P = \frac{(0.0123)\left(5.689\times10^{-2}\right)}{60} = 1.162\times10^{-5}\,\frac{\text{BTU}}{\text{SEC}}$$

The accompanying data, see pgs. 45-63, show a number of things. As they should the wire node temperatures final values vary linearly with the end node temperatures, the wire temperature is a strong function of the wire to heat sink conductance (it was varied from 10 times better to 10 times worse than that of a one inch piece of wire).

Qualitatively then it is clearly shown that keeping the heat sink temperatures down (this design incorporates a sink at each end of the motor; not just at one end) and minimizing the thermal resistance between the wire and the heat sink are vital.

An estimate of the wire to heat sink conductivity was made by assuming the following geometry.

1" long piece of Cu AWG 25 wire encapsulated



Assume a reasonable model is (of potting compound)

$$\text{Area} = \frac{0.018\text{"} \times 1\text{"}}{144 \text{in}^2 / \text{ft}^2} = 1.25 \times 10^{-4} \text{ft}^2$$

$$\text{Length} = \frac{1}{(32)(12)} = 2.6 \times 10^{-3} \text{ft}$$

Conductance per inch of wire length is found from:

(2850 KT Stykast)

$$\text{Conductivity} = 19.3\ \frac{\text{BTU}-\text{in}}{\text{Ft}^2\text{HR}^\circ\text{F}} \times \frac{1}{12}\frac{\text{Ft}}{\text{in}} = 1.61\frac{\text{BTU}}{\text{FtHR}^\circ\text{F}}$$

which compares to Cu as

$$210\frac{\text{BTU}}{\text{HRFt}^\circ\text{F}}$$

Thus the potting to Cu conductivity ratio inverse is

$$\frac{210}{1.61} = 130.6$$

$$\text{Conductance} = \text{Conductivity}\ \frac{\text{Area}}{\text{Length}}$$

$$\text{Cond.} \Rightarrow \frac{\text{BTU}}{^\circ\text{FHR}\cancel{\text{Ft}}} \times \frac{\cancel{\text{Ft}^2}}{\cancel{\text{Ft}}} \Rightarrow \frac{\text{BTU}}{^\circ\text{FHR}}$$

here for one inch of wire

$$\text{Conductance} = \frac{(1.61)(1.25\times10^{-4})}{(2.6)(10^{-3})} = 0.077\frac{\text{BTU}}{^\circ\text{FHR}}$$

or

$$0.077\frac{\text{BTU}}{^\circ\text{FHR}} \times \frac{1}{3600}\frac{\text{HR}}{\text{SEC}} = 2.15\times10^{-5}\frac{\text{BTU}}{^\circ\text{FSec}}$$

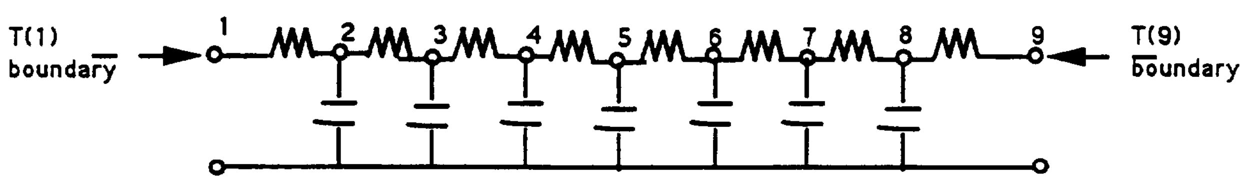
Compare to conductance of 1" of Cu wire (AWG25) from end to end which is

$$1.2795 \times 10^{-6} \frac{\text{BTU}}{\text{Sec}^{\circ}\text{F}}$$

Ratio

$$\frac{\text{CondofCmpd}}{\text{Ccu}} = \frac{2.15 \times 10^{-5}}{1.2795 \times 10^{-6}} = 16.8$$

If this can be achieved one would expect Re in the model to be somewhere between equal to Ccu and Ccu/10. The following data were run on the thermal analysis program for this case. From the results one sees that with the heat sinks held constant at 200°F, the wire started at 100°F, and the conductance from the wire to the heat sink set equal to that of 1 inch of AWG25 (end to end conductance) the final hot spot temperature of 272°F (133°C) was reached in approximately 5 minutes. 133°C is well within the insulation capacity of good grade magnet wire.



Thermal Network Used In Wire Analysis

```
752 DATA 2,7.46E-6,2,0
754 DATA 1.28E-6,1,1.28E-6,3
756 DATA 3,7.46E-6,2,0
758 DATA 1.28E-6,2,1.28E-6,4
760 DATA 4,7.46E-6,2,0
762 DATA 1.28E-6, 3, 1.28E-6, 5
764 DATA 5,7.46E-6,2,0
766 DATA 1.28E-6,4,1.28E-6,6
768 DATA 6,7.46E-6,2,0
770 DATA 1.28E-6,5,1.28E-6,7
772 DATA 7,7.46E-6,2,0
774 DATA 1.28E-6,6,1.28E-6,8
776 DATA 8,7.46E-6,2,0
778 DATA 1.28E-6,7,1.28E-6,9
780 Q(2) = 1.162E-05
782 Q(3) = 1.165E-05
784 Q(4) = 1.165E-05
786 Q(5) = 1.165E-05
788 Q(6) = 1.165E-05
790 Q(7) = 1.165E-05
792 Q(8) = 1.165E-05
794 T(1) = 200
796 T(9) = 200
```

STEADY STATE   SIGNIFICANT DIGITS= 4   RELAX ITER'NS= 14

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.772	691.462	0.000	0.000000051235634
3	254.519	714.209	0.000	0.000000125966594
4	268.183	727.873	0.000	0.000000111325612
5	272.753	732.443	0.000	0.000000082773582
6	268.223	727.913	0.000	0.000000051015277
7	254.587	714.277	0.000	0.000000025734055
8	231.846	691.536	0.000	0.000000009502783
9	200.000	659.690	0.000	0.000000000000000

Elapsed computer time with printing= 3.333333333330302D-02 minutes
Date is 02-25-1993   Time is 09:40:18

TIME= 0.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	100.000	559.690	0.000	0.000139619995025
3	100.000	559.690	0.000	0.000011649999578
4	100.000	559.690	0.000	0.000011649999578
5	100.000	559.690	0.000	0.000011649999578
6	100.000	559.690	0.000	0.000011649999578
7	100.000	559.690	0.000	0.000011649999578
8	100.000	559.690	0.000	0.000139650001074
9	200.000	659.690	0.000	0.000000000000000

TIME= 40.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	205.622	665.312	0.000	0.000001922702722
3	207.179	666.869	0.000	0.000016218846213
4	204.963	664.653	0.000	0.000004641791293
5	205.749	665.439	0.000	0.000022936137611
6	204.969	664.659	0.000	0.000004641791293
7	207.191	666.881	0.000	0.000016219080862
8	205.639	665.329	0.000	0.000001922702722
9	200.000	659.690	0.000	0.000000000000000

TIME= 80.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	223.042	682.732	0.000	0.000001318639647
3	238.489	698.179	0.000	0.000004236555014
4	247.018	706.708	0.000	0.000003183478157
5	250.029	709.719	0.000	0.000005991394573
6	247.024	706.714	0.000	0.000003183478611
7	238.501	698.191	0.000	0.000004236556379
8	223.059	682.749	0.000	0.000001318640102
9	200.000	659.690	0.000	0.000000000000000

TIME= 120.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	228.875	688.565	0.000	0.000000540234169
3	249.143	708.833	0.000	0.000001254034032
4	261.101	720.791	0.000	0.000001304240641
5	265.095	724.785	0.000	0.000001773471922
6	261.106	720.796	0.000	0.000001304240641
7	249.155	708.845	0.000	0.000001254034032
8	228.892	688.582	0.000	0.000000540234169
9	200.000	659.690	0.000	0.000000000000000

TIME= 160.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	230.837	690.527	0.000	0.000000195862242
3	252.751	712.441	0.000	0.000000398260966
4	265.838	725.528	0.000	0.000000472853259
5	270.197	729.887	0.000	0.000000563226081
6	265.844	725.534	0.000	0.000000472853259
7	252.762	712.452	0.000	0.000000398260966
8	230.855	690.545	0.000	0.000000195862242
9	200.000	659.690	0.000	0.000000000000000

```
TIME= 200.0000    RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE     TEMP - F          TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000         0.00000000000000
   2        231.498       691.188         0.000         0.00000068028399
   3        253.970       713.660         0.000         0.00000130866653
   4        267.434       727.124         0.000         0.00000164235075
   5        271.922       731.612         0.000         0.00000185073404
   6        267.440       727.130         0.000         0.00000164235075
   7        253.982       713.672         0.000         0.00000130866653
   8        231.516       691.206         0.000         0.00000068028399
   9        200.000       659.690         0.000         0.00000000000000

TIME= 240.0000    RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE     TEMP - F          TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000         0.00000000000000
   2        231.721       691.411         0.000         0.00000023233687
   3        254.382       714.072         0.000         0.00000043664503
   4        267.973       727.663         0.000         0.00000056091082
   5        272.504       732.194         0.000         0.00000061750931
   6        267.979       727.669         0.000         0.00000056091082
   7        254.394       714.084         0.000         0.00000043664503
   8        231.739       691.429         0.000         0.00000023233687
   9        200.000       659.690         0.000         0.00000000000000

TIME= 280.0000    RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE     TEMP - F          TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000         0.00000000000000
   2        231.797       691.487         0.000         0.00000007880508
   3        254.521       714.211         0.000         0.00000014665628
   4        268.155       727.845         0.000         0.00000019025229
   5        272.701       732.391         0.000         0.00000020740330
   6        268.160       727.850         0.000         0.00000019025229
   7        254.533       714.223         0.000         0.00000014665628
   8        231.814       691.504         0.000         0.00000007880508
   9        200.000       659.690         0.000         0.00000000000000

TIME= 320.0000    RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE     TEMP - F          TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000         0.00000000000000
   2        231.822       691.512         0.000         0.00000002665296
   3        254.568       714.258         0.000         0.00000004939654
   4        268.216       727.906         0.000         0.00000006434593
   5        272.767       732.457         0.000         0.00000006985725
   6        268.222       727.912         0.000         0.00000006434593
   7        254.580       714.270         0.000         0.00000004939654
   8        231.840       691.530         0.000         0.00000002665296
   9        200.000       659.690         0.000         0.00000000000000

TIME= 360.0000    RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE     TEMP - F          TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000         0.00000000000000
   2        231.831       691.521         0.000         0.00000000900358
   3        254.584       714.274         0.000         0.00000001665751
   4        268.237       727.927         0.000         0.00000002173655
   5        272.789       732.479         0.000         0.00000002355728
   6        268.242       727.932         0.000         0.00000002173655
   7        254.595       714.285         0.000         0.00000001665751
   8        231.848       691.538         0.000         0.00000000900358
   9        200.000       659.690         0.000         0.00000000000000
```

TIME= 400.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.833	691.523	0.000	0.000000000303994
3	254.589	714.279	0.000	0.000000000562008
4	268.244	727.934	0.000	0.000000000733907
5	272.797	732.487	0.000	0.000000000794799
6	268.249	727.939	0.000	0.000000000733907
7	254.601	714.291	0.000	0.000000000562008
8	231.851	691.541	0.000	0.000000000303994
9	200.000	659.690	0.000	0.000000000000000

TIME= 440.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.834	691.524	0.000	0.000000000102618
3	254.591	714.281	0.000	0.000000000189656
4	268.246	727.936	0.000	0.000000000247742
5	272.799	732.489	0.000	0.000000000268214
6	268.252	727.942	0.000	0.000000000247742
7	254.603	714.293	0.000	0.000000000189656
8	231.852	691.542	0.000	0.000000000102618
9	200.000	659.690	0.000	0.000000000000000

TIME= 480.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000034637
3	254.591	714.281	0.000	0.000000000064007
4	268.247	727.937	0.000	0.000000000083622
5	272.800	732.490	0.000	0.000000000090520
6	268.253	727.943	0.000	0.000000000083622
7	254.603	714.293	0.000	0.000000000064007
8	231.852	691.542	0.000	0.000000000034637
9	200.000	659.690	0.000	0.000000000000000

TIME= 520.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000011691
3	254.592	714.282	0.000	0.000000000021603
4	268.247	727.937	0.000	0.000000000028224
5	272.801	732.491	0.000	0.000000000030551
6	268.253	727.943	0.000	0.000000000028224
7	254.603	714.293	0.000	0.000000000021603
8	231.852	691.542	0.000	0.000000000011691
9	200.000	659.690	0.000	0.000000000000000

TIME= 560.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000003946
3	254.592	714.282	0.000	0.000000000007291
4	268.247	727.937	0.000	0.000000000009526
5	272.801	732.491	0.000	0.000000000010311
6	268.253	727.943	0.000	0.000000000009526
7	254.603	714.293	0.000	0.000000000007291
8	231.853	691.543	0.000	0.000000000003946
9	200.000	659.690	0.000	0.000000000000000

```
TIME= 600.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1          200.000        659.690          0.000           0.00000000000000
   2          231.835        691.525          0.000           0.00000000001332
   3          254.592        714.282          0.000           0.00000000002461
   4          268.247        727.937          0.000           0.00000000003215
   5          272.801        732.491          0.000           0.00000000003480
   6          268.253        727.943          0.000           0.00000000003215
   7          254.604        714.294          0.000           0.00000000002461
   8          231.853        691.543          0.000           0.00000000001332
   9          200.000        659.690          0.000           0.00000000000000

TIME= 640.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1          200.000        659.690          0.000           0.00000000000000
   2          231.835        691.525          0.000           0.00000000000449
   3          254.592        714.282          0.000           0.00000000000831
   4          268.247        727.937          0.000           0.00000000001085
   5          272.801        732.491          0.000           0.00000000001175
   6          268.253        727.943          0.000           0.00000000001085
   7          254.604        714.294          0.000           0.00000000000831
   8          231.853        691.543          0.000           0.00000000000449
   9          200.000        659.690          0.000           0.00000000000000

TIME= 680.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1          200.000        659.690          0.000           0.00000000000000
   2          231.835        691.525          0.000           0.00000000000152
   3          254.592        714.282          0.000           0.00000000000280
   4          268.247        727.937          0.000           0.00000000000366
   5          272.801        732.491          0.000           0.00000000000396
   6          268.253        727.943          0.000           0.00000000000366
   7          254.604        714.294          0.000           0.00000000000280
   8          231.853        691.543          0.000           0.00000000000152
   9          200.000        659.690          0.000           0.00000000000000

TIME= 720.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1          200.000        659.690          0.000           0.00000000000000
   2          231.835        691.525          0.000           0.00000000000051
   3          254.592        714.282          0.000           0.00000000000095
   4          268.247        727.937          0.000           0.00000000000124
   5          272.801        732.491          0.000           0.00000000000134
   6          268.253        727.943          0.000           0.00000000000124
   7          254.604        714.294          0.000           0.00000000000095
   8          231.853        691.543          0.000           0.00000000000051
   9          200.000        659.690          0.000           0.00000000000000

TIME= 760.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1          200.000        659.690          0.000           0.00000000000000
   2          231.835        691.525          0.000           0.00000000000017
   3          254.592        714.282          0.000           0.00000000000032
   4          268.247        727.937          0.000           0.00000000000042
   5          272.801        732.491          0.000           0.00000000000045
   6          268.253        727.943          0.000           0.00000000000042
   7          254.604        714.294          0.000           0.00000000000032
   8          231.853        691.543          0.000           0.00000000000017
   9          200.000        659.690          0.000           0.00000000000000
```

TIME= 800.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000000006
3	254.592	714.282	0.000	0.000000000000011
4	268.247	727.937	0.000	0.000000000000014
5	272.801	732.491	0.000	0.000000000000015
6	268.253	727.943	0.000	0.000000000000014
7	254.604	714.294	0.000	0.000000000000011
8	231.853	691.543	0.000	0.000000000000006
9	200.000	659.690	0.000	0.000000000000000

TIME= 840.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000000002
3	254.592	714.282	0.000	0.000000000000004
4	268.247	727.937	0.000	0.000000000000005
5	272.801	732.491	0.000	0.000000000000005
6	268.253	727.943	0.000	0.000000000000005
7	254.604	714.294	0.000	0.000000000000004
8	231.853	691.543	0.000	0.000000000000002
9	200.000	659.690	0.000	0.000000000000000

TIME= 880.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000000001
3	254.592	714.282	0.000	0.000000000000001
4	268.247	727.937	0.000	0.000000000000002
5	272.801	732.491	0.000	0.000000000000002
6	268.253	727.943	0.000	0.000000000000002
7	254.604	714.294	0.000	0.000000000000001
8	231.853	691.543	0.000	0.000000000000001
9	200.000	659.690	0.000	0.000000000000000

TIME= 920.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000001
5	272.801	732.491	0.000	0.000000000000001
6	268.253	727.943	0.000	0.000000000000001
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME= 960.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

```
TIME=1000.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000        659.690          0.000          0.00000000000000
   2         231.835        691.525          0.000          0.00000000000000
   3         254.592        714.282          0.000          0.00000000000000
   4         268.247        727.937          0.000          0.00000000000000
   5         272.801        732.491          0.000          0.00000000000000
   6         268.253        727.943          0.000          0.00000000000000
   7         254.604        714.294          0.000          0.00000000000000
   8         231.853        691.543          0.000          0.00000000000000
   9         200.000        659.690          0.000          0.00000000000000

TIME=1040.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000        659.690          0.000          0.00000000000000
   2         231.835        691.525          0.000          0.00000000000000
   3         254.592        714.282          0.000          0.00000000000000
   4         268.247        727.937          0.000          0.00000000000000
   5         272.801        732.491          0.000          0.00000000000000
   6         268.253        727.943          0.000          0.00000000000000
   7         254.604        714.294          0.000          0.00000000000000
   8         231.853        691.543          0.000          0.00000000000000
   9         200.000        659.690          0.000          0.00000000000000

TIME=1080.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000        659.690          0.000          0.00000000000000
   2         231.835        691.525          0.000          0.00000000000000
   3         254.592        714.282          0.000          0.00000000000000
   4         268.247        727.937          0.000          0.00000000000000
   5         272.801        732.491          0.000          0.00000000000000
   6         268.253        727.943          0.000          0.00000000000000
   7         254.604        714.294          0.000          0.00000000000000
   8         231.853        691.543          0.000          0.00000000000000
   9         200.000        659.690          0.000          0.00000000000000

TIME=1120.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000        659.690          0.000          0.00000000000000
   2         231.835        691.525          0.000          0.00000000000000
   3         254.592        714.282          0.000          0.00000000000000
   4         268.247        727.937          0.000          0.00000000000000
   5         272.801        732.491          0.000          0.00000000000000
   6         268.253        727.943          0.000          0.00000000000000
   7         254.604        714.294          0.000          0.00000000000000
   8         231.853        691.543          0.000          0.00000000000000
   9         200.000        659.690          0.000          0.00000000000000

TIME=1160.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000        659.690          0.000          0.00000000000000
   2         231.835        691.525          0.000          0.00000000000000
   3         254.592        714.282          0.000          0.00000000000000
   4         268.247        727.937          0.000          0.00000000000000
   5         272.801        732.491          0.000          0.00000000000000
   6         268.253        727.943          0.000          0.00000000000000
   7         254.604        714.294          0.000          0.00000000000000
   8         231.853        691.543          0.000          0.00000000000000
   9         200.000        659.690          0.000          0.00000000000000
```

TIME=1200.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	-0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1240.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	-0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	-0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	-0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1280.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1320.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1360.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1400.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1440.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1480.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1520.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=1560.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

```
TIME=1600.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000        0.00000000000000
   2        231.835       691.525         0.000       -0.00000000000000
   3        254.592       714.282         0.000        0.00000000000000
   4        268.247       727.937         0.000        0.00000000000000
   5        272.801       732.491         0.000        0.00000000000000
   6        268.253       727.943         0.000        0.00000000000000
   7        254.604       714.294         0.000        0.00000000000000
   8        231.853       691.543         0.000        0.00000000000000
   9        200.000       659.690         0.000        0.00000000000000

TIME=1640.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000        0.00000000000000
   2        231.835       691.525         0.000       -0.00000000000000
   3        254.592       714.282         0.000        0.00000000000000
   4        268.247       727.937         0.000        0.00000000000000
   5        272.801       732.491         0.000        0.00000000000000
   6        268.253       727.943         0.000        0.00000000000000
   7        254.604       714.294         0.000        0.00000000000000
   8        231.853       691.543         0.000        0.00000000000000
   9        200.000       659.690         0.000        0.00000000000000

TIME=1680.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000        0.00000000000000
   2        231.835       691.525         0.000       -0.00000000000000
   3        254.592       714.282         0.000        0.00000000000000
   4        268.247       727.937         0.000        0.00000000000000
   5        272.801       732.491         0.000        0.00000000000000
   6        268.253       727.943         0.000        0.00000000000000
   7        254.604       714.294         0.000        0.00000000000000
   8        231.853       691.543         0.000        0.00000000000000
   9        200.000       659.690         0.000        0.00000000000000

TIME=1720.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000        0.00000000000000
   2        231.835       691.525         0.000       -0.00000000000000
   3        254.592       714.282         0.000        0.00000000000000
   4        268.247       727.937         0.000        0.00000000000000
   5        272.801       732.491         0.000        0.00000000000000
   6        268.253       727.943         0.000        0.00000000000000
   7        254.604       714.294         0.000        0.00000000000000
   8        231.853       691.543         0.000        0.00000000000000
   9        200.000       659.690         0.000        0.00000000000000

TIME=1760.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
      NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
   1        200.000       659.690         0.000        0.00000000000000
   2        231.835       691.525         0.000       -0.00000000000000
   3        254.592       714.282         0.000        0.00000000000000
   4        268.247       727.937         0.000        0.00000000000000
   5        272.801       732.491         0.000        0.00000000000000
   6        268.253       727.943         0.000        0.00000000000000
   7        254.604       714.294         0.000        0.00000000000000
   8        231.853       691.543         0.000        0.00000000000000
   9        200.000       659.690         0.000        0.00000000000000
```

```
TIME=1800.0000     RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000         659.690          0.000         0.00000000000000
    2         231.835         691.525          0.000        -0.00000000000000
    3         254.592         714.282          0.000         0.00000000000000
    4         268.247         727.937          0.000         0.00000000000000
    5         272.801         732.491          0.000         0.00000000000000
    6         268.253         727.943          0.000         0.00000000000000
    7         254.604         714.294          0.000         0.00000000000000
    8         231.853         691.543          0.000         0.00000000000000
    9         200.000         659.690          0.000         0.00000000000000

TIME=1840.0000     RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000         659.690          0.000         0.00000000000000
    2         231.835         691.525          0.000        -0.00000000000000
    3         254.592         714.282          0.000         0.00000000000000
    4         268.247         727.937          0.000         0.00000000000000
    5         272.801         732.491          0.000         0.00000000000000
    6         268.253         727.943          0.000         0.00000000000000
    7         254.604         714.294          0.000         0.00000000000000
    8         231.853         691.543          0.000         0.00000000000000
    9         200.000         659.690          0.000         0.00000000000000

TIME=1880.0000     RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000         659.690          0.000         0.00000000000000
    2         231.835         691.525          0.000        -0.00000000000000
    3         254.592         714.282          0.000         0.00000000000000
    4         268.247         727.937          0.000         0.00000000000000
    5         272.801         732.491          0.000         0.00000000000000
    6         268.253         727.943          0.000         0.00000000000000
    7         254.604         714.294          0.000         0.00000000000000
    8         231.853         691.543          0.000         0.00000000000000
    9         200.000         659.690          0.000         0.00000000000000

TIME=1920.0000     RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000         659.690          0.000         0.00000000000000
    2         231.835         691.525          0.000        -0.00000000000000
    3         254.592         714.282          0.000         0.00000000000000
    4         268.247         727.937          0.000         0.00000000000000
    5         272.801         732.491          0.000         0.00000000000000
    6         268.253         727.943          0.000         0.00000000000000
    7         254.604         714.294          0.000         0.00000000000000
    8         231.853         691.543          0.000         0.00000000000000
    9         200.000         659.690          0.000         0.00000000000000

TIME=1960.0000     RCMIN=   2.91406     MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000         659.690          0.000         0.00000000000000
    2         231.835         691.525          0.000        -0.00000000000000
    3         254.592         714.282          0.000         0.00000000000000
    4         268.247         727.937          0.000         0.00000000000000
    5         272.801         732.491          0.000         0.00000000000000
    6         268.253         727.943          0.000         0.00000000000000
    7         254.604         714.294          0.000         0.00000000000000
    8         231.853         691.543          0.000         0.00000000000000
    9         200.000         659.690          0.000         0.00000000000000
```

TIME=2000.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2040.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2080.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2120.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2160.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2000.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=2040.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=2080.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=2120.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=2160.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.00000000000000
2	231.835	691.525	0.000	-0.00000000000000
3	254.592	714.282	0.000	0.00000000000000
4	268.247	727.937	0.000	0.00000000000000
5	272.801	732.491	0.000	0.00000000000000
6	268.253	727.943	0.000	0.00000000000000
7	254.604	714.294	0.000	0.00000000000000
8	231.853	691.543	0.000	0.00000000000000
9	200.000	659.690	0.000	0.00000000000000

TIME=2200.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2240.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2280.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2320.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

TIME=2360.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

```
TIME=2400.0000    RCMIN=  2.91406      MIN NODE # 8      ITERATIONS= 0
      NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1        200.000        659.690          0.000          0.00000000000000
   2        231.835        691.525          0.000         -0.00000000000000
   3        254.592        714.282          0.000          0.00000000000000
   4        268.247        727.937          0.000          0.00000000000000
   5        272.801        732.491          0.000          0.00000000000000
   6        268.253        727.943          0.000          0.00000000000000
   7        254.604        714.294          0.000          0.00000000000000
   8        231.853        691.543          0.000          0.00000000000000
   9        200.000        659.690          0.000          0.00000000000000

TIME=2440.0000    RCMIN=  2.91406      MIN NODE # 8      ITERATIONS= 0
      NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1        200.000        659.690          0.000          0.00000000000000
   2        231.835        691.525          0.000         -0.00000000000000
   3        254.592        714.282          0.000          0.00000000000000
   4        268.247        727.937          0.000          0.00000000000000
   5        272.801        732.491          0.000          0.00000000000000
   6        268.253        727.943          0.000          0.00000000000000
   7        254.604        714.294          0.000          0.00000000000000
   8        231.853        691.543          0.000          0.00000000000000
   9        200.000        659.690          0.000          0.00000000000000

TIME=2480.0000    RCMIN=  2.91406      MIN NODE # 8      ITERATIONS= 0
      NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1        200.000        659.690          0.000          0.00000000000000
   2        231.835        691.525          0.000         -0.00000000000000
   3        254.592        714.282          0.000          0.00000000000000
   4        268.247        727.937          0.000          0.00000000000000
   5        272.801        732.491          0.000          0.00000000000000
   6        268.253        727.943          0.000          0.00000000000000
   7        254.604        714.294          0.000          0.00000000000000
   8        231.853        691.543          0.000          0.00000000000000
   9        200.000        659.690          0.000          0.00000000000000

TIME=2520.0000    RCMIN=  2.91406      MIN NODE # 8      ITERATIONS= 0
      NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1        200.000        659.690          0.000          0.00000000000000
   2        231.835        691.525          0.000         -0.00000000000000
   3        254.592        714.282          0.000          0.00000000000000
   4        268.247        727.937          0.000          0.00000000000000
   5        272.801        732.491          0.000          0.00000000000000
   6        268.253        727.943          0.000          0.00000000000000
   7        254.604        714.294          0.000          0.00000000000000
   8        231.853        691.543          0.000          0.00000000000000
   9        200.000        659.690          0.000          0.00000000000000

TIME=2560.0000    RCMIN=  2.91406      MIN NODE # 8      ITERATIONS= 0
      NODE     TEMP - F          TEMP - R          Q-INPUT Q-NET
   1        200.000        659.690          0.000          0.00000000000000
   2        231.835        691.525          0.000         -0.00000000000000
   3        254.592        714.282          0.000          0.00000000000000
   4        268.247        727.937          0.000          0.00000000000000
   5        272.801        732.491          0.000          0.00000000000000
   6        268.253        727.943          0.000          0.00000000000000
   7        254.604        714.294          0.000          0.00000000000000
   8        231.853        691.543          0.000          0.00000000000000
   9        200.000        659.690          0.000          0.00000000000000
```

```
TIME=2600.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
     NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000       659.690          0.000           0.00000000000000
   2         231.835       691.525          0.000          -0.00000000000000
   3         254.592       714.282          0.000           0.00000000000000
   4         268.247       727.937          0.000           0.00000000000000
   5         272.801       732.491          0.000           0.00000000000000
   6         268.253       727.943          0.000           0.00000000000000
   7         254.604       714.294          0.000           0.00000000000000
   8         231.853       691.543          0.000           0.00000000000000
   9         200.000       659.690          0.000           0.00000000000000

TIME=2640.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
     NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000       659.690          0.000           0.00000000000000
   2         231.835       691.525          0.000          -0.00000000000000
   3         254.592       714.282          0.000           0.00000000000000
   4         268.247       727.937          0.000           0.00000000000000
   5         272.801       732.491          0.000           0.00000000000000
   6         268.253       727.943          0.000           0.00000000000000
   7         254.604       714.294          0.000           0.00000000000000
   8         231.853       691.543          0.000           0.00000000000000
   9         200.000       659.690          0.000           0.00000000000000

TIME=2680.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
     NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000       659.690          0.000           0.00000000000000
   2         231.835       691.525          0.000          -0.00000000000000
   3         254.592       714.282          0.000           0.00000000000000
   4         268.247       727.937          0.000           0.00000000000000
   5         272.801       732.491          0.000           0.00000000000000
   6         268.253       727.943          0.000           0.00000000000000
   7         254.604       714.294          0.000           0.00000000000000
   8         231.853       691.543          0.000           0.00000000000000
   9         200.000       659.690          0.000           0.00000000000000

TIME=2720.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
     NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000       659.690          0.000           0.00000000000000
   2         231.835       691.525          0.000          -0.00000000000000
   3         254.592       714.282          0.000           0.00000000000000
   4         268.247       727.937          0.000           0.00000000000000
   5         272.801       732.491          0.000           0.00000000000000
   6         268.253       727.943          0.000           0.00000000000000
   7         254.604       714.294          0.000           0.00000000000000
   8         231.853       691.543          0.000           0.00000000000000
   9         200.000       659.690          0.000           0.00000000000000

TIME=2760.0000    RCMIN=  2.91406     MIN NODE # 8     ITERATIONS= 0
     NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
   1         200.000       659.690          0.000           0.00000000000000
   2         231.835       691.525          0.000          -0.00000000000000
   3         254.592       714.282          0.000           0.00000000000000
   4         268.247       727.937          0.000           0.00000000000000
   5         272.801       732.491          0.000           0.00000000000000
   6         268.253       727.943          0.000           0.00000000000000
   7         254.604       714.294          0.000           0.00000000000000
   8         231.853       691.543          0.000           0.00000000000000
   9         200.000       659.690          0.000           0.00000000000000
```

```
TIME=2800.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000       659.690           0.000         0.00000000000000
    2         231.835       691.525           0.000        -0.00000000000000
    3         254.592       714.282           0.000         0.00000000000000
    4         268.247       727.937           0.000         0.00000000000000
    5         272.801       732.491           0.000         0.00000000000000
    6         268.253       727.943           0.000         0.00000000000000
    7         254.604       714.294           0.000         0.00000000000000
    8         231.853       691.543           0.000         0.00000000000000
    9         200.000       659.690           0.000         0.00000000000000

TIME=2840.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000       659.690           0.000         0.00000000000000
    2         231.835       691.525           0.000        -0.00000000000000
    3         254.592       714.282           0.000         0.00000000000000
    4         268.247       727.937           0.000         0.00000000000000
    5         272.801       732.491           0.000         0.00000000000000
    6         268.253       727.943           0.000         0.00000000000000
    7         254.604       714.294           0.000         0.00000000000000
    8         231.853       691.543           0.000         0.00000000000000
    9         200.000       659.690           0.000         0.00000000000000

TIME=2880.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000       659.690           0.000         0.00000000000000
    2         231.835       691.525           0.000        -0.00000000000000
    3         254.592       714.282           0.000         0.00000000000000
    4         268.247       727.937           0.000         0.00000000000000
    5         272.801       732.491           0.000         0.00000000000000
    6         268.253       727.943           0.000         0.00000000000000
    7         254.604       714.294           0.000         0.00000000000000
    8         231.853       691.543           0.000         0.00000000000000
    9         200.000       659.690           0.000         0.00000000000000

TIME=2920.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000       659.690           0.000         0.00000000000000
    2         231.835       691.525           0.000        -0.00000000000000
    3         254.592       714.282           0.000         0.00000000000000
    4         268.247       727.937           0.000         0.00000000000000
    5         272.801       732.491           0.000         0.00000000000000
    6         268.253       727.943           0.000         0.00000000000000
    7         254.604       714.294           0.000         0.00000000000000
    8         231.853       691.543           0.000         0.00000000000000
    9         200.000       659.690           0.000         0.00000000000000

TIME=2960.0000     RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
       NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
    1         200.000       659.690           0.000         0.00000000000000
    2         231.835       691.525           0.000        -0.00000000000000
    3         254.592       714.282           0.000         0.00000000000000
    4         268.247       727.937           0.000         0.00000000000000
    5         272.801       732.491           0.000         0.00000000000000
    6         268.253       727.943           0.000         0.00000000000000
    7         254.604       714.294           0.000         0.00000000000000
    8         231.853       691.543           0.000         0.00000000000000
    9         200.000       659.690           0.000         0.00000000000000
```

TIME=3000.0000 RCMIN= 2.91406 MIN NODE # 8 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	200.000	659.690	0.000	0.000000000000000
2	231.835	691.525	0.000	-0.000000000000000
3	254.592	714.282	0.000	0.000000000000000
4	268.247	727.937	0.000	0.000000000000000
5	272.801	732.491	0.000	0.000000000000000
6	268.253	727.943	0.000	0.000000000000000
7	254.604	714.294	0.000	0.000000000000000
8	231.853	691.543	0.000	0.000000000000000
9	200.000	659.690	0.000	0.000000000000000

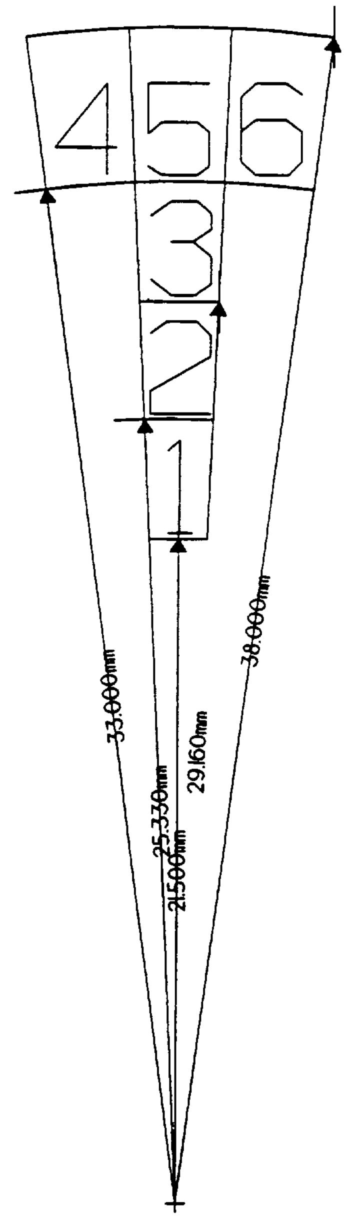
```
Elapsed computer time with printing= 1.383333333333326 minutes
Date is 02-25-1993     Time is 09:46:24
752 DATA 2,7.46E-6,2,0
754 DATA 1.28E-6,1,1.28E-6,3
756 DATA 3,7.46E-6,2,0
758 DATA 1.28E-6,2,1.28E-6,4
760 DATA 4,7.46E-6,2,0
762 DATA 1.28E-6, 3, 1.28E-6, 5
764 DATA 5,7.46E-6,2,0
766 DATA 1.28E-6,4,1.28E-6,6
768 DATA 6,7.46E-6,2,0
770 DATA 1.28E-6,5,1.28E-6,7
772 DATA 7,7.46E-6,2,0
774 DATA 1.28E-6,6,1.28E-6,8
776 DATA 8,7.46E-6,2,0
778 DATA 1.28E-6,7,1.28E-6,9
780 Q(2) = 1.162E-05
    Q(3) = 1.165E-05
    Q(4) = 1.165E-05
786 Q(5) = 1.165E-05
```

Appendix C:

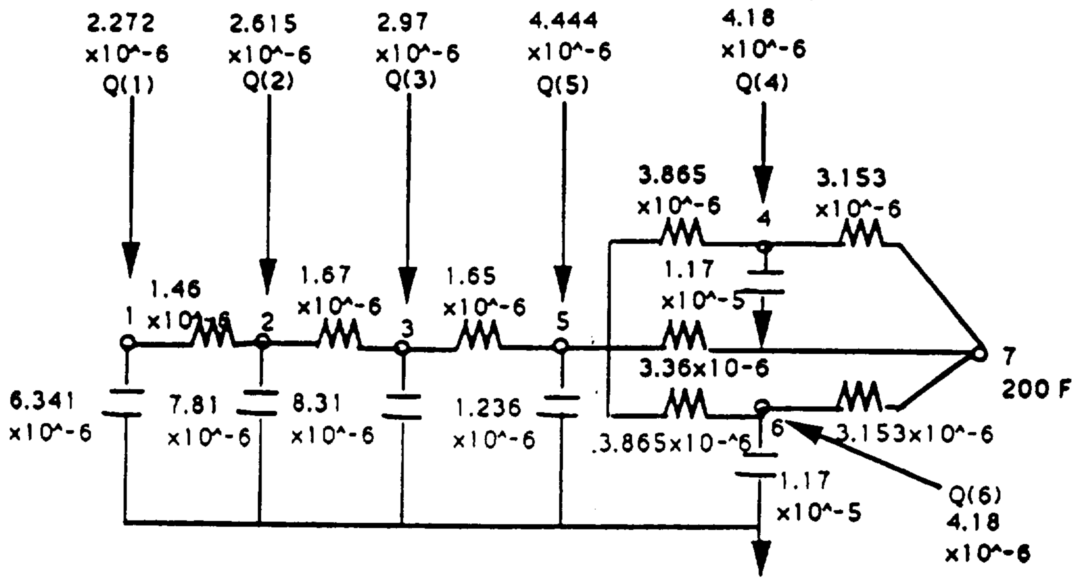
Core or Iron Loss Considerations:

Because this motor will be used in the servo application for TVC it will not in use experience much rotation and hence, in use, will not experience much core loss. However, during development, test and checkout it will be subjected to cyclic test, frequency response experiments and the like which will cause core loss.

This analysis was carried out as follows. It was assumed that the motor was rotating at 20,000 rpm and that this caused a sine wave of flux at a temporal frequency of 1333HZ. For the four pole motor, this should be a worst case by far. The separation of hysteresis and eddy current losses is difficult and not often attempted. Instead manufactures' data are used. These data are derived in turn from test. Data from reference fourteen was cross checked with other data in reference six. From these references it was estimated that the core loss of this material at 1330HZ would be 45.35 watts per pound of material. The final four pole configuration was then divided into 24 identical segments. Each segment consisted of one tooth and the adjoining back iron half way to each of the adjacent teeth. A planar analysis was performed under the assumption that all heat flow of consequence will be radial because of the deliberately high axial thermal resistance in the stator stack (put there also to inhibit eddy current losses, which vary approximately as the thickness of the lamination squared). The use of the one twenty fourth segment is justified on the basis of symmetry i.e. all the segments are heating evenly and hence all heat flow must be radial. The segment was divided into six pieces and a lumped thermal network constructed as shown below.



Lamination Core Loss
Geometric Model



Core Loss Thermal Network

In the network above the initial dimensions are in millimeters but these were converted to feet in the calculations and the dimensions of the thermal conductance are

$$\frac{\text{BTU}}{\text{sec}^\circ\text{F}}$$

the dimensions of the thermal capacity are

$$\frac{\text{BTU}}{^\circ\text{F}}$$

and the entering power in

$$\frac{\text{BTU}}{\text{sec}}$$

All temperatures are Fahrenheit. From the diagrams it is seen that the outermost part of the stator was assumed to be at 200°F for the analysis. The rest of this appendix contains the network analyzer results and the input file used to characterize the network (see last sheet, lines 752 to 788). Both steady state and transient numerical analyses were performed.

STEADY STATE SIGNIFICANT DIGITS= 4 RELAX ITER'NS= 12

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	211.745	671.435	0.000	-0.000000030378878
2	210.182	669.872	0.000	-0.000000033029913
3	207.241	666.931	0.000	-0.000000038733759
4	201.958	661.648	0.000	0.000000007822710
5	202.473	662.163	0.000	-0.000000014680492
6	201.958	661.648	0.000	0.000000007822710
7	200.000	659.690	0.000	0.000000000000000

Elapsed computer time with printing= 3.333333333333144D-02 minutes
Date is 02-26-1993 Time is 03:58:50

```
TIME=   0.0000     RCMIN=  0.97017    MIN NODE # 5     ITERATIONS= 0
        NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
    1        100.000       559.690          0.000           0.000002272000074
    2        100.000       559.690          0.000           0.000002615000085
    3        100.000       559.690          0.000           0.000002969999969
    4        100.000       559.690          0.000           0.000319479993777
    5        100.000       559.690          0.000           0.000340439990396
    6        100.000       559.690          0.000           0.000319479993777
    7        200.000       659.690          0.000           0.000000000000000

TIME=  40.0000     RCMIN=  0.97017      MIN NODE # 5     ITERATIONS= 0
        NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
    1        181.143       640.833          0.000           0.000007742999514
    2        184.844       644.534          0.000           0.000007898842341
    3        191.201       650.891          0.000           0.000005324476206
    4        199.929       659.619          0.000           0.000000949694368
    5        199.034       658.724          0.000           0.000001700159146
    6        199.929       659.619          0.000           0.000000949694368
    7        200.000       659.690          0.000           0.000000000000000

TIME=  80.0000     RCMIN=  0.97017      MIN NODE # 5     ITERATIONS= 0
        NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
    1        205.635       665.325          0.000           0.000001540642529
    2        205.125       664.815          0.000           0.000001571254188
    3        204.046       663.736          0.000           0.000001058745056
    4        201.554       661.244          0.000           0.000000188528631
    5        201.789       661.479          0.000           0.000000337766863
    6        201.554       661.244          0.000           0.000000188528631
    7        200.000       659.690          0.000           0.000000000000000
```

TIME= 120.0000 RCMIN= 0.97017 MIN NODE # 5 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	210.508	670.198	0.000	0.000000306474334
2	209.160	668.850	0.000	0.000000312563827
3	206.601	666.291	0.000	0.000000210612242
4	201.878	661.568	0.000	0.000000037503302
5	202.337	662.027	0.000	0.000000067190712
6	201.878	661.568	0.000	0.000000037503302
7	200.000	659.690	0.000	0.000000000000000

TIME= 160.0000 RCMIN= 0.97017 MIN NODE # 5 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	211.477	671.167	0.000	0.000000060965810
2	209.962	669.652	0.000	0.000000062177165
3	207.109	666.799	0.000	0.000000041896318
4	201.942	661.632	0.000	0.000000007460393
5	202.446	662.136	0.000	0.000000013366001
6	201.942	661.632	0.000	0.000000007460393
7	200.000	659.690	0.000	0.000000000000000

TIME= 200.0000 RCMIN= 0.97017 MIN NODE # 5 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	211.670	671.360	0.000	0.000000012127704
2	210.122	669.812	0.000	0.000000012368675
3	207.210	666.900	0.000	0.000000008334280
4	201.955	661.645	0.000	0.000000001484069
5	202.468	662.158	0.000	0.000000002658849
6	201.955	661.645	0.000	0.000000001484069
7	200.000	659.690	0.000	0.000000000000000

TIME= 240.0000 RCMIN= 0.97017 MIN NODE # 5 ITERATIONS= 0

NODE	TEMP - F	TEMP - R	Q-INPUT	Q-NET
1	211.708	671.398	0.000	0.000000002412520
2	210.154	669.844	0.000	0.000000002460455
3	207.230	666.920	0.000	0.000000001657908
4	201.957	661.647	0.000	0.000000000295220
5	202.472	662.162	0.000	0.000000000528915
6	201.957	661.647	0.000	0.000000000295220
7	200.000	659.690	0.000	0.000000000000000

```
TIME= 280.0000    RCMIN=   0.97017     MIN NODE # 5     ITERATIONS= 0
       NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
   1         211.716       671.406         0.000         0.000000000479914
   2         210.160       669.850         0.000         0.000000000489449
   3         207.234       666.924         0.000         0.000000000329801
   4         201.958       661.648         0.000         0.000000000058727
   5         202.473       662.163         0.000         0.000000000105215
   6         201.958       661.648         0.000         0.000000000058727
   7         200.000       659.690         0.000         0.000000000000000

TIME= 320.0000    RCMIN=   0.97017     MIN NODE # 5     ITERATIONS= 0
       NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
   1         211.717       671.407         0.000         0.000000000095467
   2         210.161       669.851         0.000         0.000000000097364
   3         207.235       666.925         0.000         0.000000000065606
   4         201.958       661.648         0.000         0.000000000011682
   5         202.473       662.163         0.000         0.000000000020930
   6         201.958       661.648         0.000         0.000000000011682
   7         200.000       659.690         0.000         0.000000000000000

TIME= 360.0000    RCMIN=   0.97017     MIN NODE # 5     ITERATIONS= 0
       NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
   1         211.718       671.408         0.000         0.000000000018991
   2         210.162       669.852         0.000         0.000000000019368
   3         207.235       666.925         0.000         0.000000000013051
   4         201.958       661.648         0.000         0.000000000002324
   5         202.473       662.163         0.000         0.000000000004164
   6         201.958       661.648         0.000         0.000000000002324
   7         200.000       659.690         0.000         0.000000000000000

TIME= 400.0000    RCMIN=   0.97017     MIN NODE # 5     ITERATIONS= 0
       NODE     TEMP - F         TEMP - R          Q-INPUT Q-NET
   1         211.718       671.408         0.000         0.000000000003778
   2         210.162       669.852         0.000         0.000000000003853
   3         207.235       666.925         0.000         0.000000000002596
   4         201.958       661.648         0.000         0.000000000000462
   5         202.473       662.163         0.000         0.000000000000828
   6         201.958       661.648         0.000         0.000000000000462
   7         200.000       659.690         0.000         0.000000000000000

Elapsed computer time with printing= .8833333333333258 minutes
Date is 02-26-1993      Time is 04:03:12
```

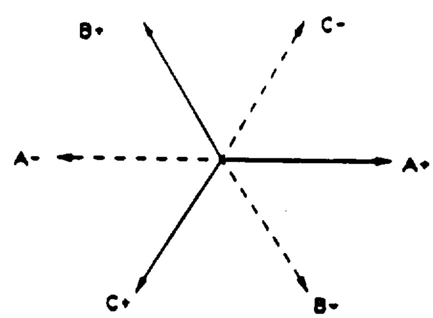
```
752  DATA 1,6.341E-6,1,0
754  DATA 1.46E-6,2
756  DATA 2,7.81E-6,2,0
758  DATA 1.46E-6,1,1.67E-6,3
760  DATA 3, 8.31E-6,2,0
762  DATA 1.67E-6,2,1.65E-6,5
764  DATA 5,1.236E-5,4,0
766  DATA 1.65E-6,3,3.865E-6,4,3.36E-6,7,3.865E-6,6
768  DATA 4,1.17E-5,2,0
770  DATA 3.865E-6, 5,3.153E-6,7
772  DATA 6, 1.17E-5,2,0
774  DATA 3.865E-6,5,3.153E-6,7
776  T(7) = 200
778  Q(1) = 2.272E-06
780  Q(2) = 2.615E-06
782  Q(3) = 2.97E-06
784  Q(5) = 4.44E-06
786  Q(4) = 4.18E-06
788  Q(6) = 4.18E-06
```

Appendix D:

Winding Considerations

There are a number of ways to depict winding information. The one preferred by this author is used below. It is assumed that a double layer i.e. two coils per slot winding is used. Because the lap and wave windings are electrically identical the choice between them is best left to the particular winding shop.

First lay out a series of slots according to the number decided upon. In the bottom of the slot diagram fill the slots according to the slot star with the rotation CCW or in the positive angle direction.



SLOT STAR

If a full pitch winding were being used both the top and the bottom of the slot would be carrying the same phase current. If as is the case shown here on the next page the coils are to be short pitched by one slot they will span 5 slots rather than the 6 slots required for the full pitch case. This may easily be depicted by sliding the top row of conductors one slot to the left from its position in the full pitch case. The resulting diagram is shown on the next page.

		→ Pole 4					Pole 1						Pole 2						Pole 3				Pole 4 →	
Upper	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+
Lower	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+
Slot No.	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Winding Diagram of 3 Phase

Four Pole Short Pitched Motor

Stator Winding

The mmf resulting from such a winding may be depicted by assigning current magnitudes to the various phases (these magnitudes correspond to balanced 3 phase values e.g. A+=1, B+=-1/2, C+=-1/2, A-=-1, B-=1/2, C-=1/2). Then treat each slot as if the total current in that slot is the weight of an impulse and plot these impulses in the same position as each slot. Next integrate spatially all the impulses and plot the results after having made the average of the mmf zero. A computer program was written to do this. It is written in C and produces Mathcad plot files. Thus a C compiler and Mathcad are needed to run it. A listing is included below and a sample output is included.

```
/*      This program calculates the MMF for an integer motor winding
        and creates files for the Mathcad program wind.mcd.

        Variable Definition:

                idisp = displacement of upper windings from lower
                        winding.  idisp = 0 implies a full pitch
                        winding.  idisp = 1 implies a winding short
                        pitched by one slot.
                mmf = the magnetomotive force.
                iap = current in the the A+ phase
                icm = current in the C- phase
                ibp = current in the B+ phase
                iam = current in the A- phase
                icp = current in the C+ phase
                ibm = current in the B- phase
                phi = the phase angle of the A+ phase in degrees
                ampl = the amplitude of the currents
                current[i] = the magnitude of the ith current
                nslots = number of slots
                nspp = number of slots per pole
                nspppp = number of slots per pole per phase
                npoles = number of poles
                deg = conversion from degrees to radians
                ncases = number of cases; program allows calculation of
                         up to 5 mmf's.
                icase = case counter
                                                                        */
#include <stdio.h>
#include <math.h>
#include <conio.h>

#define         PI 3.14159265
#define         deg PI/180.
void    main(void)
{
        int     nslots, nspp, nspppp, islot, ib, it, ipole, iphase;
        int     npoles, i, icase, ncases, idisp, ip;
        float   current[7], phi, ampl, mmf[201], iap, icm, ibp;
        float   iam, icp, ibm, ibot[201], itop[201];
        FILE    *inp, *out1, *out2, *out3, *out4, *out5;

        inp = fopen("c:\\fort\\winding.in","r");
        out1 = fopen("c:\\fort\\mmf1.out","w");
        out2 = fopen("c:\\fort\\mmf2.out","w");
        out3 = fopen("c:\\fort\\mmf3.out","w");
        out4 = fopen("c:\\fort\\mmf4.out","w");
        out5 = fopen("c:\\fort\\mmf5.out","w");


        fscanf(inp," %d %d %d\n",&ncases, &nslots, &npoles);

        for(icase = 1; icase <= ncases; icase++)
        {
           fscanf(inp,"%f  %f  %d\n",
                      &phi, &ampl, &idisp);
           nspp = nslots/npoles;     /*  # of slots per pole  */
           nspppp = nspp/3;          /*  # of slots per pole per phase */

           iap = ampl*cos(phi*deg);
```

```
icm = ampl*cos((phi + 60.)*deg);
ibp = ampl*cos((phi + 120.)*deg);
iam = -iap;
icp = -icm;
ibm = -ibp;

current[1] = iap;
current[2] = icm;
current[3] = ibp;
current[4] = iam;
current[5] = icp;
current[6] = ibm;

for (ipole = 1; ipole <= npoles; ipole += 2)
{
   for(iphase = 1; iphase <= 3; iphase++)
   {
       for(islot = 1; islot <= nspppp; islot++)
       {
          ib = (ipole - 1)*nspppp*3 + (iphase - 1)*nspppp + islot;
          ibot[ib] = current[iphase];
       }
    }
}

 for (ipole = 2; ipole <= npoles; ipole +=2)
 {
    for(iphase = 4; iphase <= 6; iphase++)
    {
       for(islot = 1; islot <= nspppp; islot++)
       {
          ib = (ipole - 1)*nspppp*3 + (iphase - 4)*nspppp + islot;
          ibot[ib] = current[iphase];
       }
    }
 }

 for (ipole = 1; ipole <= npoles; ipole +=2)
 {
    for(iphase = 4; iphase <= 6; iphase++)
    {
      for(islot = 1; islot <= nspppp; islot++)
      {
         ib = (ipole - 1)*nspppp*3 + (iphase - 4)*nspppp + islot;
         ib = ib + nspp - idisp;
         if (ib > nslots)
            ib = ib - nslots;
         itop[ib] = current[iphase];
      }
   }
}

for (ipole = 2; ipole <= npoles; ipole += 2)
{
   for (iphase = 1; iphase <= 3; iphase++)
   {
      for (islot = 1; islot <= nspppp; islot++)
      {
         ib = (ipole - 1)*nspppp*3 + (iphase - 1)*nspppp + islot;
         ib = ib + nspp - idisp;
```

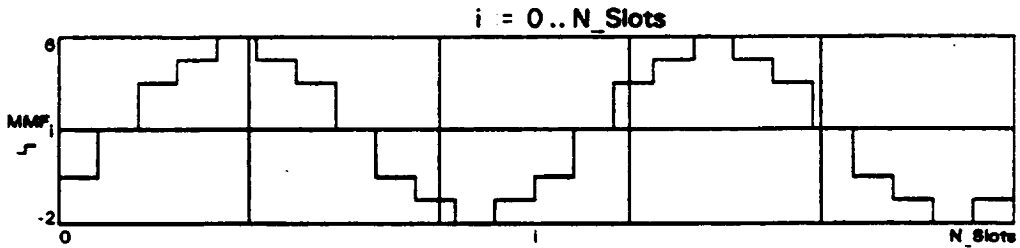
```
                    if (ib > nslots)
                       ib = ib - nslots;
                    itop[ib] = current[iphase];
                 }
              }
           }

           mmf[0] = 0.;
           for (islot = 1; islot <= nslots; islot++)
           {
              mmf[islot] = mmf[islot - 1] + ibot[islot] + itop[islot];
           }

           switch (icase)
           {
               case 1:
                  for(i = 0; i <= nslots; i++)
                     fprintf(out1," %f\n", mmf[i]);
                  break;
               case 2:
                  for(i = 0; i <= nslots; i++)
                     fprintf(out2," %f\n", mmf[i]);
                  break;
               case 3:
                  for(i = 0; i <= nslots; i++)
                     fprintf(out3," %f\n", mmf[i]);
                  break;
               case 4:
                  for(i = 0; i <= nslots; i++)
                     fprintf(out4," %f\n", mmf[i]);
                  break;
               case 5:
                  for(i = 0; i <= nslots; i++)
                     fprintf(out5," %f\n", mmf[i]);
                  break;
           }
        }
        fcloseall();
}
```

```
 5  24  4
      0. 1. 0
      30. 1. 0
      60. 1. 0
      90. 1. 0
      120. 1. 0 0.000000
2.000000
4.000000
5.000000
6.000000
5.000000
 000000
2.000000
0.000000
-1.000000
-2.000000
```

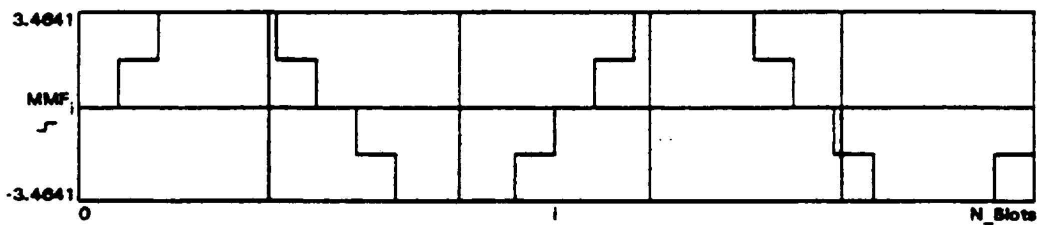
-1.000000
0.000000
2.000000
4.000000
)00000
6.000000
5.000000
4.000000
2.000000
0.000000
-1.000000
-2.000000
-1.000000
0.000000

MMF := READPRN(MMF1 $_{OUT}$)   N_Slots := length(MMF) - 1

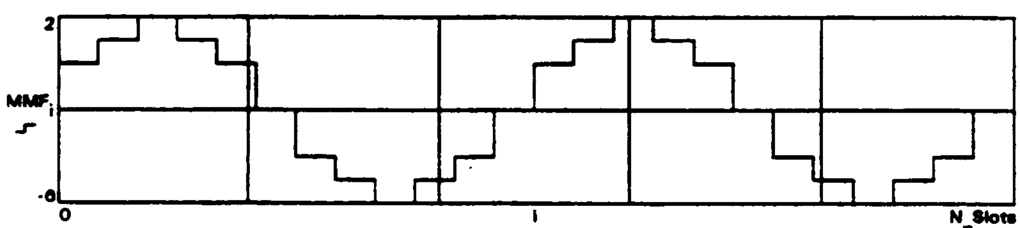
i := 0 .. N_Slots



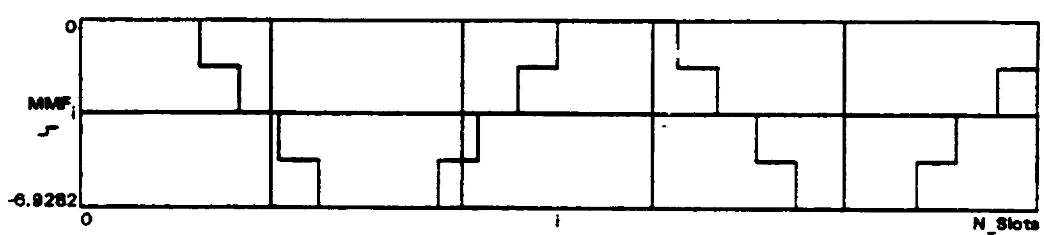
MMF := READPRN(MMF2 $_{OUT}$)



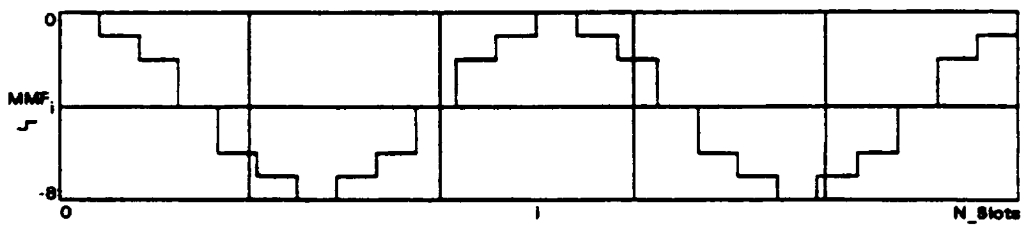
MMF := READPRN(MMF3 $_{OUT}$)



MMF := READPRN(MMF4 $_{OUT}$)



MMF := READPRN(MMF5 $_{OUT}$)



0
MMF
-8
0
i
N_Slots

APPENDIX E

Magnetic Potential Calculations

This appendix contains the spread sheet which takes the averaged data from each side of the slots and for a 7 inch long rotor turning at 10,000 rpm produces the voltage that would be induced in a one turn full pitch coil of the 4 pole configuration. The maximum value of this voltage is used to determine the number of turns in the windings as explained in the main body of the text.

A average (We/m Degree)	Delta A (We/m Degree)	Electric Force (We/m s)	Back EMF (Volts)
7.56E-03	-1.50E-05	-0.90423486	-0.321545916
3.49E-03	-5.05E-05	-3.0383145	-1.080424636
-1.34E-03	4.05E-08	0.00243486	0.000865836
-5.82E-03	-7.85E-06	-0.47176164	-0.167758439
-1.02E-02	-2.11E-04	-12.68213364	-4.509766722
-8.68E-03	-5.29E-04	-31.79548404	-11.30647412
7.57E-03	2.61E-06	0.15673284	0.055734198
3.54E-03	4.96E-05	2.9808999	1.060008004
-1.34E-03	1.17E-07	0.0070641	0.002511994
-5.82E-03	-8.03E-06	-0.48300408	-0.171756251
-1.00E-02	-2.37E-04	-14.24657628	-5.066082525
-8.15E-03	-5.36E-04	-32.21596332	-11.45599656
7.57E-03	3.95E-06	0.23759424	0.084488512
3.49E-03	-1.81E-07	-0.01088172	-0.00386954
-1.34E-03	2.27E-07	0.01361718	0.004842269
-5.81E-03	-8.00E-06	-0.4808097	-0.170975929
-9.76E-03	-2.62E-04	-15.75477666	-5.60239858
-7.61E-03	-5.41E-04	-32.55281568	-11.57578126
7.56E-03	6.05E-06	0.36384624	0.129383723
3.49E-03	2.12E-07	0.01274544	0.004532278
-1.34E-03	3.65E-07	0.02191374	0.007792526
-5.80E-03	-7.93E-06	-0.47672154	-0.16952218
-9.50E-03	-2.87E-04	-17.28317736	-6.145897869
-7.07E-03	-5.46E-04	-32.81067036	-11.66747438
7.56E-03	9.09E-06	0.54643068	0.19431075
3.49E-03	7.62E-07	0.04581144	0.016290548
-1.34E-03	4.78E-07	0.02873736	0.010219005
-5.79E-03	-8.65E-06	-0.519878682	-0.184868859
-9.21E-03	-3.14E-04	-18.88140744	-6.714228486
-6.53E-03	-5.49E-04	-33.00630084	-11.73704058

7.55E-03	1.31E-04	7.852086828	2.792202076
3.49E-03	1.38E-04	8.31829338	2.957985126
-1.34E-03	1.38E-04	8.27197092	2.941512859
-5.78E-03	1.17E-04	7.018429842	2.495753652
-8.90E-03	-2.12E-04	-12.7224441	-4.524101122
-5.98E-03	-4.09E-04	-24.5597715	-8.733454745
7.42E-03	1.33E-04	7.974803772	2.835840221
3.35E-03	1.38E-04	8.29147986	2.948450238
-1.48E-03	1.37E-04	8.21452626	2.921085538
-5.90E-03	1.07E-04	6.421399164	2.283449543
-8.69E-03	-2.39E-04	-14.35948164	-5.106231671
-5.57E-03	-4.08E-04	-24.51519252	-8.71760246
7.29E-03	1.34E-04	8.04655098	2.861353528
3.21E-03	1.37E-04	8.26175052	2.937878485
-1.62E-03	1.36E-04	8.14764276	2.897301765
-6.01E-03	1.06E-04	6.354521676	2.259667908
-8.45E-03	-2.67E-04	-16.02796194	-5.699543266
-5.16E-03	-4.08E-04	-24.5028078	-8.713198454
7.15E-03	1.35E-04	8.09022816	2.876885134
3.08E-03	1.37E-04	8.2200573	2.923052376
-1.75E-03	1.34E-04	8.05875534	2.865693399
-6.11E-03	8.83E-05	5.30925732	1.887971903
-8.18E-03	-2.94E-04	-17.67380706	-6.284805791
-4.75E-03	-4.08E-04	-24.54374952	-8.727757329
7.02E-03	1.35E-04	8.108685	2.883448386
2.94E-03	1.36E-04	8.16781302	2.90447431
-1.89E-03	1.32E-04	7.94924676	2.826752148
-6.20E-03	7.02E-05	4.221927	1.501317241
-7.89E-03	-3.20E-04	-19.25679672	-6.847716914
-4.34E-03	-4.10E-04	-24.63353874	-8.759686376
6.88E-03	1.35E-04	8.12134026	2.887948596

2.80E-03	1.35E-04	8.114697	2.885586253
-2.02E-03	1.30E-04	7.83330534	2.785523379
-6.27E-03	4.81E-05	2.89035918	1.027811724
-7.57E-03	-3.44E-04	-20.69423586	-7.358870272
-3.93E-03	-4.12E-04	-24.76159434	-8.805222947
6.75E-03	1.12E-04	6.70734792	2.38513292
2.67E-03	1.34E-04	8.07375528	2.871027378
-2.15E-03	1.29E-04	7.74970848	2.755796335
-6.32E-03	2.30E-05	1.38507462	0.492532535
-7.22E-03	-3.64E-04	-21.90090438	-7.787961598
-3.52E-03	-4.14E-04	-24.89923908	-8.854169417
6.64E-03	1.61E-04	9.67715568	3.44119656
2.53E-03	1.34E-04	8.05514814	2.864410679
-2.28E-03	1.27E-04	7.63902756	2.7164382
-6.34E-03	-3.74E-06	-0.22460832	-0.079870719
-6.86E-03	-3.80E-04	-22.8221532	-8.115557678
-3.11E-03	-4.16E-04	-25.02834678	-8.900080115
6.48E-03	1.39E-04	8.36497656	2.974585665
2.40E-03	1.34E-04	8.06440662	2.867702994
-2.41E-03	1.27E-04	7.62826608	2.712611418
-6.34E-03	-3.15E-05	-1.89293832	-0.673128867
-6.48E-03	-3.91E-04	-23.50740096	-8.359231781
-2.69E-03	-4.18E-04	-25.1501499	-8.943393304
6.34E-03	1.42E-04	8.54061714	3.037043455
2.27E-03	1.35E-04	8.09446662	2.87839233
-2.53E-03	1.27E-04	7.63262478	2.714161372
-6.31E-03	-5.91E-05	-3.55528638	-1.264259837
-6.09E-03	-3.99E-04	-23.95785006	-8.519411481
-2.27E-03	-4.20E-04	-25.25725368	-8.981479409
0.006193924	0.000270539	16.26480468	5.783764544
0.002130953	0.000279142	16.78198698	5.96767457

-0.002660178	0.000271864	16.34446368	5.812091285
-0.00624756	4.8416E-05	2.91076992	1.035069784
-0.005690403	-0.000271289	-16.30989468	-5.799798548
-0.001853978	-0.000279929	-16.82933148	-5.984510274
0.005923385	0.000549735	33.0500682	11.75260425
0.001851811	0.000560453	33.69443436	11.98174086
-0.002932042	0.000544818	32.7544281	11.64747463
-0.006295976	1.9739E-05	1.18670868	0.421993607
-0.005419114	-0.00055018	-33.07685166	-11.76212845
-0.001574049	-0.000561526	-33.75891306	-12.00466948
0.00537365	0.000553562	33.28014744	11.83442043
0.001291358	0.000559357	33.62853983	11.95830876
-0.003476859	0.000535774	32.21073288	11.45413661
-0.006315715	-7.96955E-05	-4.79129346	-1.703783954
-0.004868933	-0.000553492	-33.27593904	-11.83292392
-0.001012523	-0.000560805	-33.71560562	-11.98926936
0.004820088	0.000552277	33.20289324	11.80694884
0.000732001	0.000554953	33.36378939	11.86416351
-0.004012633	0.000513318	30.8606481	10.97404646
-0.00623602	-0.000189054	-11.36592648	-4.041723456
-0.004315441	-0.000552176	-33.19682112	-11.80478959
-0.000451718	-0.000557933	-33.54291392	-11.92786019
0.004267811	0.000551228	33.13982736	11.78452261
0.000177048	0.000549825	33.05546698	11.75452406
-0.004525951	0.000471742	28.36112904	10.08521749
-0.006046966	-0.000301038	-18.0983745	-6.435781972
-0.003763265	-0.000551296	-33.14391552	-11.78597636
0.000106215	-0.000555889	-33.42004067	-11.88416646
0.003716583	0.000275756	16.57845072	5.895297076
-0.000372777	0.000272913	16.40751453	5.834512167
-0.004997693	0.000211009	12.68583102	4.511081511

-0.005745928	-0.000189408	-11.38720896	-4.049291506
-0.003211969	-0.000275923	-16.5884607	-5.898856625
0.000662104	-0.000277691	-16.69478593	-5.936665875
0.003440827			
-0.00064569			
-0.005208701			
-0.00555652			
-0.002936047			
0.000939795			

APPENDIX F

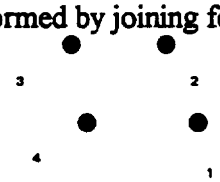
Explanation of ANSYS44A Code for File MTRM15A (Six Pole Motor)

The following program listing represents one sixth of the motor that was designed. This is a valid representation not only because the motor is symmetrical, but also because the analysis at all times spans one full pole. The electromagnetic flux that follows the air gap path between the stator and the magnet produces a torque, which effectively can be calculated by performing a line integral over that path. By definition, magnetic flux follows a closed path, so on either side of the motor, the magnetic flux should be equal and of opposite sign, therefore negating any contributions of flux on the sides of a pole to torque. The torque then, that a motor experiences may be calculated by summing up the line integral over a path in the air gap for a single pole to get a torque per pole value, and for a total torque value, multiplying the unit torque by the number of poles.

ANSYS44A was instrumental in the simulation of this motor because of its ability to handle the nonlinear material properties inherent in magnetic materials. The code breaks up the design in several phases. The first of these phases is to define the material types by assigning numbers to materials and properties to the material numbers to be used in the analysis. Material one is defined to be air, and material two is the rotor iron (Carpenter HI-MU 49). When considering the rotor iron and also the magnets (materials 3 and 4, which represent magnetization outward and inward respectively, MAGNEQUENCH MQ3-30H), the nonlinear properties of the materials must be included. This is accomplished by providing a BH curve for ANSYS44A to use, for each material posessing magnetic properties. In addition to these properties, for the magnets coercivity must be entered. For all of the material whether linear or nonlinear, the density of each material must be entered. A different material number was assigned to each phase of the windings: A+ A-, B+ B-, and C+ C-.

The next phase in this model was to create the nodes for the motor (see accompanying figure). This is accomplished by setting nodal limits. The radii from the center of the shaft to a material or shape change determine the limits. R0 is the radius of the rotor shaft. R1 is the radius to the bottom of the magnets. R2 is the radius to the bottom of the air gap. R3 is the radius to the bottom of the shoes. R4 is the radius to the top of the shoes. R5 is the radius to the top of the slots. Finally, R6 is the radius to the outer motor. Nodes between the radii limits are generated from R0 to R1, R1 to R2, etc., such that there are a total of 31 nodes from R0 to R6. It is important to have several elements in the air gap in the radial direction so that torque can be calculated accurately. For this model, five nodes in the air gap providing 4 elements was deemed sufficient.

Once the basic node pattern has been established along the radial direction, this pattern is copied along the theta direction for 60 degrees. Sixty degrees is calculated by dividing the number of elements per magnet, plus the air gap elements between magnets by the number of poles. The width of each element is one degree and the motor spans 360 degrees. Therefore, because this is a six pole motor simulation, 60 degrees is the sector of the motor over which the calculation is being done. The number of teeth per sector is found by dividing the number of elements per sector by the number of degrees per tooth (60/15), four slots per sector. The element type used for this model is the quadrilateral. Selecting a material number, for example, material two, is necessary to put the proper materials in their respective places, otherwise the default material number is one, which is air. Elements are formed by joining four nodes in this order:



This pattern is repeated along the radial node path from element 1,2,33,32,1 to element 30,31,62,61,30, by the command egen. Next, this swath of elements is copied along the theta direction for 60 degrees to generate all of the elements for the simulation. All

elements were generated initially as rotor iron simply because the majority of the motor is composed of HI-MU 49. The other parts of the motor such as: magnets, shoes, slots, and air gaps are formed by literally punching out a section of the HI-MU 49 and replacing it with those materials over the range of elements for which they span.

The elements for the air gap were modified next by selecting the material number one, the nodal path that bounds the air gap in both the r and theta direction, and finally selecting all the elements within those bounds and modifying them to be composed of air. This procedure is also repeated for the magnets, shoes, and slots. The materials were assigned colors, to see if each material was in its correct place.

For a finite element program solving the magnetostatic equations, the natural boundary condition (BC) is the zero Neumann boundary condition. This means that if a BC is not specified, the one applied is the zero normal derivative of the magnetic vector potential. This boundary condition is clearly not desired at the outer edge of the back iron because it implies that the flux is perpendicular to the outer edge of the stator. The appropriate BC is to fix the magnetic vector potential. Usually, the potential is set to zero.

The appropriate BC at the inner shaft is not so easy to understand, but the condition that is commonly used is also the zero vector potential. Actually, the solution is not sensitive to the inner BC.

The final phase was the actual analysis of the model. ANSYS44A uses the Maxwell Stress Tensor to determine the maximum torque in these electromagnetic models. The result of which shows that the maximum torque occurs in the air gap when the flux is at a maximum and is directed at 45 degrees. ANSYS44A calculates and stores the magnetic flux by first having been given a convergence criterion and a maximum number of load steps in which to reach this criterion by means of iteration. Once the iteration at which the solution converges has been isolated, that load step is written as the final load step and is saved to FILE12 for further analysis in the ANSYS44A post

processor (POST1). Once the solution is completed in the post processor, it can be used to calculate the torque by performing a line integral between the magnetic flux and the length vector over a specified nodal path in the air gap.

These operations, once the initial model has been created can either be run interactively or in batch mode. In the interactive mode, a single simulation, it takes anywhere from 25 to 45 minutes. This is understandable because the magnetic flux must be evaluated at every node, and there are 1891 nodes and 1800 elements. In the batch mode, all of the steps are preprogrammed and all that is necessary to analyze the model is to submit the batch job. The IBM 3084 system takes about the same amount of time to run the batch job as the interactive, however, the batch job does not require constant human monitoring. Another advantage to the batch mode is that as many as four jobs at a time can be submitted. This is important because to show a fully developed torque curve, the model must be simulated at a range of rotor angles. Usually this requires at least 25 angular displacements.

PROGRAM LISTING OF A 6 POLE 3" OD MOTOR
DESIGN FOR ANSYS44A

```
/CORE,5800000
/COM,ANSYS REVISION 4.4A  UP419  97    13.9922   11/14/1991
/TITLE, EMA MOTOR ANALYSIS
/PREP7
KAN,-1
KAY, 9, 1
ET,1,13,,,,1
KNL,1
NLSIZE,300
/COM,
/COM, MATERIAL 1 IS AIR
/COM,
NL,1,57,1
/COM,
/COM, MATERIAL 2 IS THE ROTOR IRON - CARPENTER HI-MU 49
/COM,
NLTAB,2,5
MP,DENS,2,8249
NLX,,1,10.,15.,20.,25.,30.,35.
NLX,,,40,45,50,55,60,65
NLX,,,70,75,80,85,90,95
NLX,,,100,795.8
NLY,,,,.947,1.052,1.083,1.102,1.117,1.130
NLY,,,,1.140,1.147,1.155,1.164,1.172,1.181
NLY,,,,1.189,1.195,1.201,1.206,1.212,1.218
NLY,,,,1.222,1.5
/SHOW,4208
/COM,
/COM, DEFINE MAGNET CURVE AS MATERIALS 3 & 4
/COM, MAGNETIZATION OUTWARD FOR 3, INWARD FOR 4
/COM, MATERIAL - MAGNEQUENCH  MQ3-F 30H
/COM,
CSYS,1
NLTAB,3,5
MP,DENS,3,7550
NLX,,1,31800,827600
NLY,,1,,.06,1.13
HC = -827600
NL,3,109,HC
NL,3,163,0
NLTAB,4,5
MP,DENS,4,7550
NLX,,1,31800,827600
NLY,,1,,0.06,1.13
HC = 827600
NL,4,109,HC
NL,4,163,0.
/COM,
/COM, MATERIALS 5 THROUGH 10 ARE A+, A-, B+, B-,
/COM, C+, AND C- SOURCES RESPECTIVELY
/COM,
NL,5,55,1
NL,6,55,1
NL,7,55,1
NL,8,55,1
NL,9,55,1
NL,10,55,1
/COM,
/COM, THET = THETA ORIENTATION OF ROTORS MEASURED TO LEADING
/COM,      EDGE OF OUTWARDLY MAGNETIZED MAGNET
/COM, NTEE = NUMBER OF TEETH
/COM, NMAG = NUMBER OF MAGNETS
/COM, NTHE = NUMBER OF ELEMENTS IN THE THETA DIRECTION
/COM,
/COM, R0 = RADIUS IN METERS FROM CENTER TO OUTSIDE OF THE SHAFT
/COM, R1 = RADIUS TO BASE OF MAGNET
/COM, R2 = RADIUS TO THE TOP OF THE MAGNET
/COM, R3 = RADIUS TO TOOTH SHOE AT AIR GAP
```

```
/COM, R4 = RADIUS TO END OF TOOTH AT THE SHOE
/COM, R5 = RADIUS TO BACK IRON
/COM, R6 = OUTER RADIUS OF THE MOTOR
/COM,
THET = -15.
NTEE = 36
NMAG = 6
NTHE = 360
R0 = 0.005
R1 = 0.01118
R2 = 0.02118
R3 = 0.02218
R4 = 0.02252
R5 = 0.03429
R6 = 0.03810
NR01 = 5
NR12 = 9
NR23 = 5
NR34 = 2
NR45 = 5
NR56 = 4
NTR1 = (NR01 + 1)
NTR2 = NTR1 + NR12
NTR3 = NTR2 + NR23
NTR4 = NTR3 + NR34
NTR5 = NTR4 + NR45
NTR6 = NTR5 + NR56
THMG = 50
/COM,
/COM, THMA = NUMBER OF ELEMENTS PER MAGNET + AIR GAP BETWEEN
/COM, NTPC = NUMBER OF TEETH PER SECTOR OVER WHICH THE CALCULATION
/COM,      IS DONE
/COM,
THMA = NTHE/NMAG
THPT = NTHE/NTEE
NTPS = THMA/THPT
N,1,R0
N,NTR1,R1
FILL,1,NTR1
N,NTR2,R2
FILL,NTR1,NTR2
N,NTR3,R3
FILL,NTR2,NTR3
N,NTR4,R4
FILL,NTR3,NTR4
N,NTR5,R5
FILL,NTR4,NTR5
N,NTR6,R6
FILL,NTR5,NTR6
DTHE = (360/NTHE)
/COM, THMX = MAXIMUM THETA OVER WHICH WE ARE DOING THE CALCULATION
THMX = NTHE/NMAG
NELT = (THMX/DTHE)
NGEN,(NELT+1),NTR6,1,NTR6,1.,0.,DTHE
/COM,
/COM, GENERATE ALL ELEMENTS AS ROTOR IRON
/COM,
NALL $EALL
MAT,2
N1 = 1
N2 = 2
N3 = (NTR6 + 2)
N4 = (NTR6 + 1)
E,N1,N2,N3,N4
ETR6 = (NTR6 - 1)
EGEN,ETR6,1,1,1
EGEN,NELT,NTR6,1,ETR6,1
/COM,
/COM, MODIFY ELEMENTS FOR AIR GAP
/COM,
EPS = .00001
```

```
138. MAT,1
139. NSEL,X,(R2-EPS),R3
140. ENODE,1
141. EMODIF,ALL
142. EALL $NALL
143. /COM,
144. /COM, NOW DO THE MAGNETS - AIR
145. /COM,
146. MAT,3
147. NSEL,X,(R1-EPS),R2
148. ENODE,1
149. EMODIF,ALL
150. MAT,1
151. T1 = THMG + THET - EPS
152. T2 = THMA + THET + EPS
153. NRSEL,Y,T1,T2
154. ENODE,1 $EMODIF, ALL
155. NALL $EALL
156. THEA = THMA - THMG
157. T1 = THET - THEA - EPS
158. T2 = THET + EPS
159. NSEL,X,(R1 - EPS),R2
160. NRSEL,Y,T1,T2
161. ENODE,1   $EMODIF,ALL
162. NALL $EALL
163. NSEL,X,(R1 - EPS),R2
164. T1 = THET - THMA - THEA - EPS
165. T2 = THET - THMA + EPS
166. NRSEL,Y,T1,T2
167. ENODE,1   $EMODIF,ALL
168. NALL $EALL
169. MAT,4
170. T1 = THET - THMA - EPS
171. T2 = THET - THEA + EPS
172. NSEL,X,(R1 - EPS),R2 $NRSEL,Y,T1,T2
173. ENODE,1 $EMODIF,ALL
174. NALL $EALL
175. T1 = THMA + THET - EPS
176. T2 = THMA + THMG + THET + EPS
177. NSEL,X,(R1 - EPS),R2 $NRSEL,Y,T1,T2
178. ENODE,1 $EMODIF,ALL
179. NALL $EALL
180. /COM,
181. /COM, SHOES - AIR
182. /COM,
183. MAT,1
184. /COM, THSH = 8.202
185. /COM, THSA = 11.122
186. THSH = 8 $THSA = 10
187. THAR = THSA - THSH
188. T1 = THSH/2   $T1 = T1 - EPS
189. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
190. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2   $ENODE,1
191. EMODIF,ALL
192. EALL $NALL
193. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
194. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
195. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
196. NALL $EALL
197. T1 = T2 + THSH $T2 = T1 + THAR $T1 = T1 - EPS $T1 = T1 - EPS
198. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
199. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
200. EALL $NALL
201. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
202. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
203. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
204. NALL $EALL
205. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
206. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
207. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
208. NALL $EALL
```

```
T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
NALL $EALL
/PNUM,MAT,1 $/NUMBER,1
/COM,
/COM, FIND  R THAT DIVIDES THE AREA FOR THE UPPER AND
/COM, LOWER WINDING INTO EQUAL AREAS
/COM,
T1 = (R5*R5) $T2 = (R4*R4) $T3 = ((T1+T2)/2)
R = SQRT(T3) $DR45 = (R5 - R4)/NR45  $D452 = DR45/2
/COM, *****
/COM, THT = THETA WIDTH OF A TOOTH (NOT INCLUDING SHOE)
/COM, THC = THETA WIDTH OF CONDUCTOR
/COM, THT = 4.331 $THC = 6.791
THT = 4 $THC = 6
/COM,
/COM, INSERT THE A+ MATERIAL IN THE BOTTOM OF SLOTS 1 & 2
/COM, THE C- MATERIAL IN THE BOTTOM OF SLOTS 3 & 4
/COM, AND THE B+ MATERIAL IN THE BOTTOM OF SLOTS 5 & 6
/COM,SLOT #1
MAT,5
T1 = THT/2  $T2 = T1 + THC + EPS $T1 = T1 - EPS
NSEL,X,(R - EPS),(R5 + EPS) $NRSEL,Y,T1,T2
ENODE,1 $EMODIF,ALL
NALL $EALL
/COM,SLOT #2
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
$ENODE,1 $EMODIF,ALL
NALL $EALL
/COM, SLOT #3
MAT,10
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
ENODE,1 $EMODIF,ALL
NALL $EALL
/COM,SLOT #4
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
ENODE,1  $EMODIF,ALL
NALL  $EALL
/COM, SLOT #5
MAT,7
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
ENODE,1  $EMODIF,ALL
NALL $EALL
/COM,SLOT #6
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
ENODE,1  $EMODIF,ALL
NALL  $EALL
/COM,
/COM, NOW INSERT THE A+ MATERIAL IN THE TOP OF SLOTS 1 & 2
/COM, THE C- MATERIAL IN THE TOP OF SLOTS 3 & 4
/COM, AND THE B+ MATERIAL IN THE TOP OF SLOTS 5 & 6
/COM, NEW MODIFICATIONS ON 1/26/93 INDICATE FULL PITCH WINDINGS
/COM,SLOT #2
MAT,5
T1 = THT*1.5+THC-EPS $T2 = T1 + THC + 2*EPS
NSEL,X,(R4 - EPS),(R+D452) $NRSEL,Y,T1,T2
ENODE,1 $EMODIF,ALL
NALL $EALL
/COM,SLOT #3
MAT,10
T1 = T2 + THT - 2*EPS  $T2 = T1 + THC + 2*EPS
NSEL,X,(R4-EPS),(R+D452)  $NRSEL,Y,T1,T2
ENODE,1 $EMODIF,ALL
NALL  $EALL
/COM,SLOT #4
```

```
MAT,10
T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
NSEL,X,(R4-EPS),(R+D452) $NRSEL,Y,T1,T2
ENODE,1 $EMODIF,ALL
NALL $EALL
/COM,SLOT #5
MAT,7
T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
NSEL,X,(R4-EPS),(R+D452) $NRSEL,Y,T1,T2
ENODE,2 $EMODIF,ALL
NALL $EALL
/COM,SLOT #6
MAT,7
T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
NSEL,X,(R4-EPS),(R+D452) $NRSEL,Y,T1,T2
$ENODE,1 $EMODIF,ALL
/COM,SLOT #1
NALL $EALL
MAT,5
T1 = THT/2 - EPS $T2 = T1 + THC + 2*EPS
NSEL,X,(R4-EPS),(R+D452) $NRSEL,Y,T1,T2
$ENODE,1 $EMODIF,ALL
NALL $EALL
/PNUM,MAT,1 $/COLOR,1,CYAN $/COLOR,2,BLUE   $/COLOR,3,RED
/COLOR,4,MAGENTA $/COLOR,5,MRED  $/COLOR,6,BMAGENT
/COLOR,7,CBLUE $/COLOR,8,GCYAN $/COLOR,9,GREEN $/COLOR,10,GREEN
/NUMBER,1 $NALL $EALL
/COM,
/COM, ENTER BOUNDARY CONDITIONS
/COM,
NSEL,X,R0
NT,ALL,MAG,0
NALL $EALL
NSEL,X,R6
NT,ALL,MAG,0
NALL $EALL
CE,1,0,1,MAG,1,1861,MAG,1
RP30,1,,1,,,1
/COM,
/COM, ENTER THE CURRENTS
/COM,
JAPL = 8.E6
JBPL = -4.0E6
JCPL = -4.0E6
JAM = -JAPL $JBM = -JBPL $JCM = -JCPL
KTEMP,-1
NALL $EALL
ESEL,MAT,5 $TE,ALL,,JAPL
NALL $EALL
ESEL,MAT,6 $TE,ALL,,JBPL $/COM,SHOULD BE
NALL $EALL
ESEL,MAT,7 $TE,ALL,,JCPL
NALL $EALL
ESEL,MAT,8 $TE,ALL,,JAM
NALL $EALL
ESEL,MAT,9 $TE,ALL,,JBM
NALL $EALL
ESEL,MAT,10 $TE,ALL,,JCM
NALL $EALL
KBC,0
ITER,10
LWRITE
ITER,-20,,2
CNVR,0.0001 $KBC,1
LWRITE $AFWRI
FINI
/EXEC
/INPUT,27
FINI
/EOF
```

APPENDIX G

Experimental Thermal Investigation

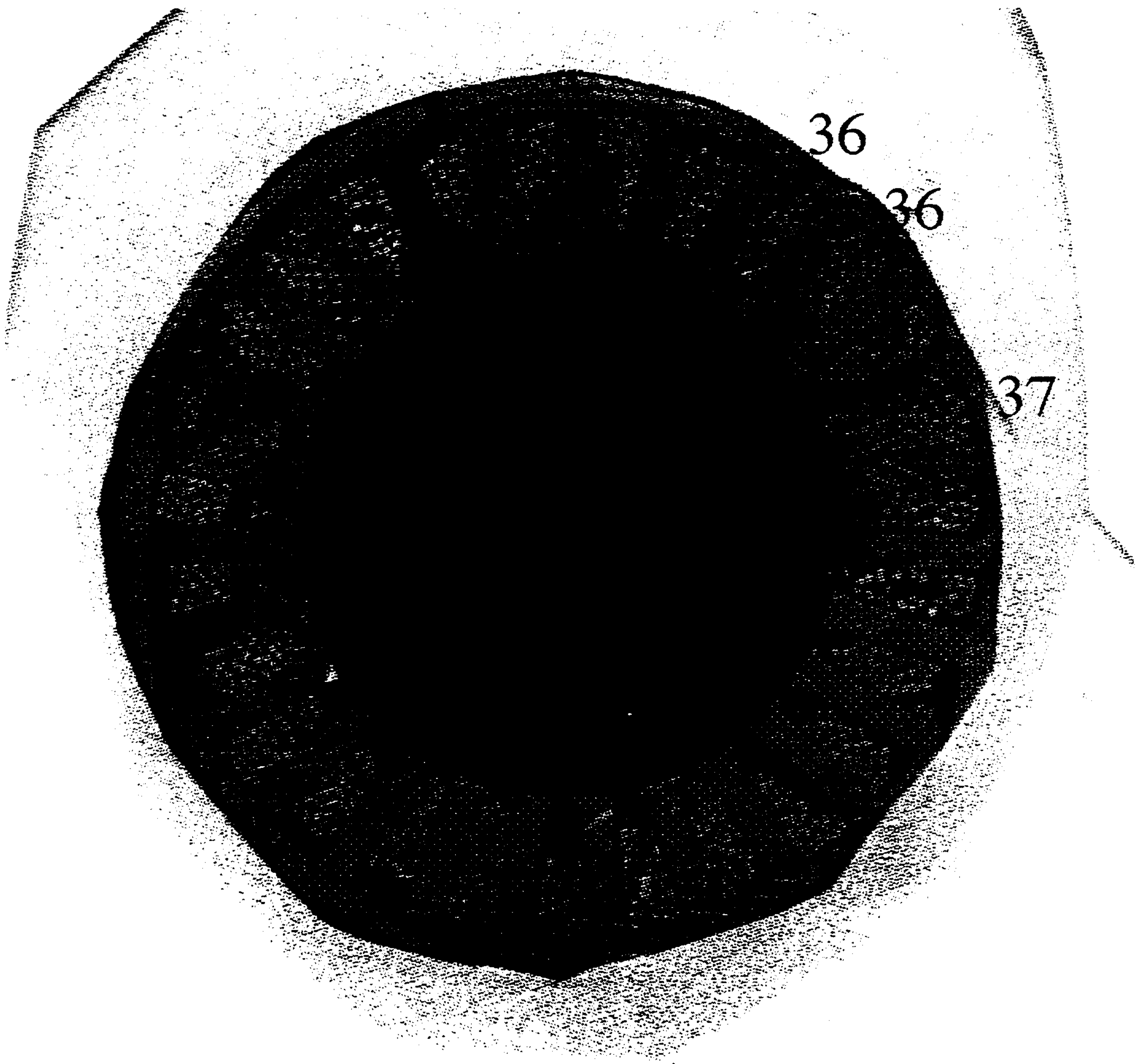
To start to become familiar with techniques and problems to be encountered in future laboratory work a commercially available motor was obtained and subsequently opened i.e. the end bells removed. From this first phase it was observed that there were eight poles and twenty seven slots. Thus it is immediately clear that this is a fractional slot motor i.e. there is no integer by which the product of the number of phases and the number of poles will equal 27. It was interesting to see that the manufacturer had used extended end windings on *one* end of the motor and carefully formed them so that they fit tightly into the aluminum end bell (without however any potting). Based on our later work this is, no doubt, to facilitate heat removal. Next the end windings on one end were cut off more or less flush with the first laminations in the stator stack. A 600 dpi color scan was made of the end of the lamination stack and is enclosed as figure on p. 99 below. The numbers beside some of the slots denote the numbers of conductors in the various slots. From their varying numbers it is clear, as expected, that this fractional slot motor does not have identical coils. Thus its electrical balance is assured from careful design of the unbalanced windings. The diameter of the wire was measured several times and it approximates 25 AWG but not exactly.

Perhaps the wire is a metric size (this is a pure speculation). Three Hall effect devices were found to be cemented to the inside of the assembly where the magnetic flux from the rotor's permanent magnets can sweep over them. The angular distance between them corresponded to the standard required for electronic commutation purposes. Additional things to be noticed include the fact that there is no apparent effort made to encapsulate the wires in the slots. This is a little surprising because it is common commercial practice to vacuum impregnate the windings with insulating varnish after they are placed in the stator. In this instance where heat removal was pretty clearly a design feature the voids in the slots is a little puzzling (or perhaps it is felt that the large end turns and so forth are enough of a heat removal design feature to make the motor competitive). Analysis of the fuller slots showed that the fill factor achieved in this motor does not exceed 50% (a common number it appears). The stator laminations measured to be 25 mils thick. This is a little surprising because 14 mil material is generally available (10 mil material appears to be available in a few cases). However in the light of our core loss analysis perhaps core loss is just not that big a problem and possibly the thicker material is more easily fabricated than the thinner.

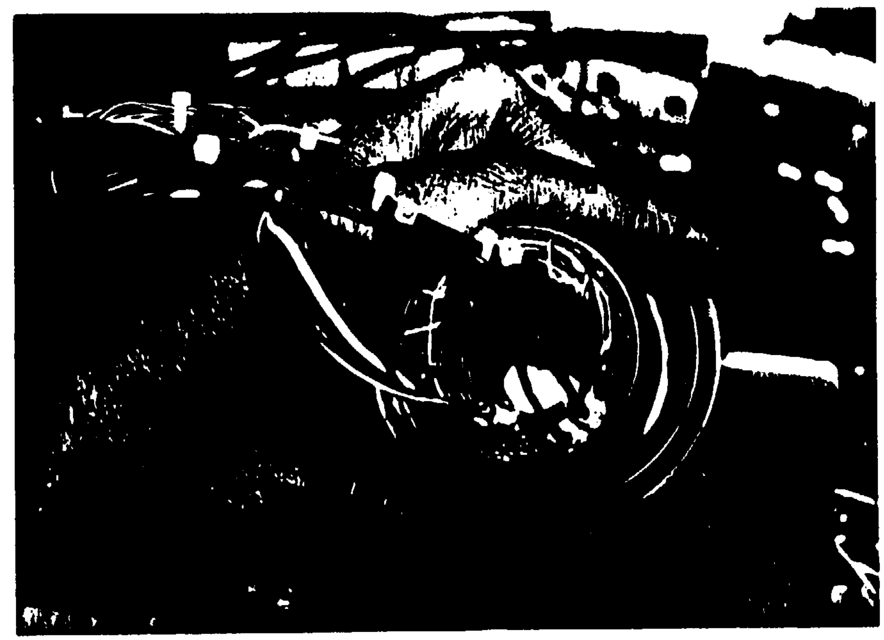
After this examination it was decided to perform a simple thermal test on the motor. The motor was fixed to the bottom of a plastic jar with RTV. Thermocouples were cemented along the length of the inside of the stator and to the copper end windings (black and white photographs). The first thermocouple was placed 1/4 inch up from the bottom of the stack, the second 3/8, third 3/4, fourth 1 1/8, fifth 1 1/2, and the last two on the copper at the top of the motor. With a known ambient temperature as an initial condition an ice and water combination was poured into the plastic jar i.e. surrounding the outside of the motor and the output of the thermocouples recorded on a floppy disk. The results of this exercise are presented in the multiline multicolored figure on p. 101 showing temperature at the various stations versus time.

While the exponential appearing changes in the various temperatures confirms the nature of the response and agrees with the lumped thermal circuit approach to modeling one thing stands out that is somewhat counterintuitive (at least to this author without the benefit of a thermal simulation of this configuration). That is the temperature of the copper followed the temperature of the iron without any appreciable time lag. While there is at present no explanation of this observed fact speculation must center on two things. The first speculation is that there is better than anticipated iron to copper wire thermal coupling (despite the visible voids in the slots). The second speculation is that the relatively small thermal capacitance of the copper (compared to the relatively massive iron presence) makes it possible for its temperature to track the iron temperature closely in time.

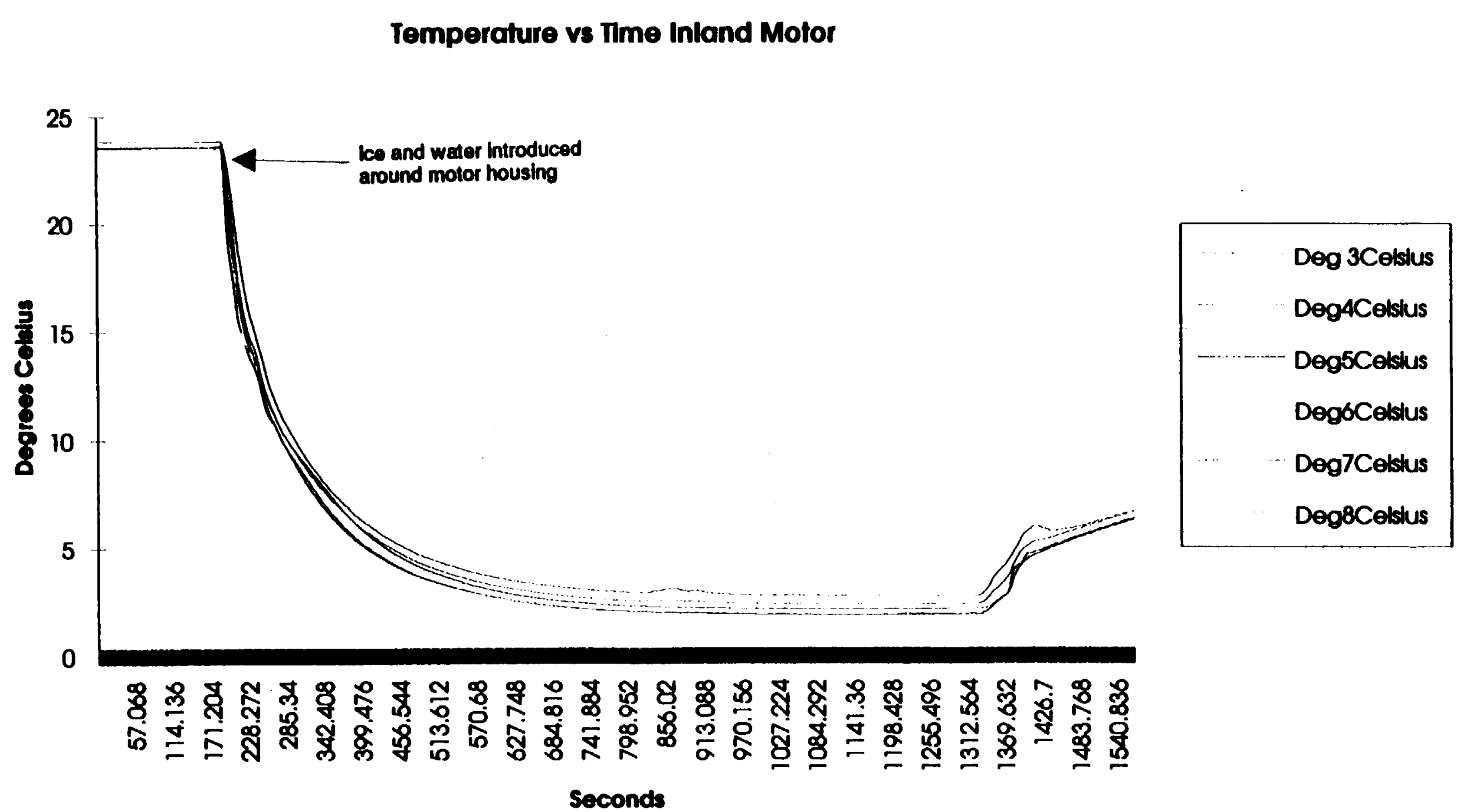
Several possibilities for instrumenting the fabricated motors arise from this experiment. To perform meaningful thermal characterization of the new motors temperature measurements must be made in several contexts. Of course thermal measurement wires should be wound with the main windings (this need only require a single strand). During laboratory tests essentially the same experiment described above should be run with refinements gained from this work. One experiment might involve thermocouples cemented to the iron and the copper as before. However instead of not only cooling the outer part of the stator and seeing how heat leaves the motor in an attempt to characterize the thermal circuit but also the copper winding would be energized to determine its temperature profile with time. Another test to be done is to spin the unenergized motor with another motor and measure its temperature rise and, if possible, the power transmitted into the motor. This test would establish the core loss caused by spinning the permanent magnets relative to the stator and confirm hopefully that it is a small contributor.


36
36
37

Laboratory Setup For Thermal Motor Tests



View of Motor Showing Thermocouple Placement


Temperature vs Time Inland Motor
Degrees Celsius
25
20
15
10
5
0
Ice and water introduced
around motor housing
57.068
114.136
171.204
228.272
285.34
342.408
399.476
456.544
513.612
570.68
627.748
684.816
741.884
798.952
856.02
913.088
970.156
1027.224
1084.292
1141.36
1198.428
1255.496
1312.564
1369.632
1426.7
1483.768
1540.836
Seconds
Deg 3Celsius
Deg4Celsius
Deg5Celsius
Deg6Celsius
Deg7Celsius
Deg8Celsius

K120[illegible]2A.PRN

Measurement 9		Meas 3								
DC Volts			Seconds	Deg 3Celsi	Deg4Celsiu	Deg5Celsiu	Deg6Celsiu	Deg7Celsiu	Deg8Celsius	
	1	0.028	2.594	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	2	0.0279	5.188	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	3	0.028	7.782	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	4	0.0279	10.376	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	5	0.0279	12.97	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	6	0.0279	15.564	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	7	0.0279	18.158	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	8	0.0279	20.752	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	9	0.0279	23.346	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	10	0.0279	25.94	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	11	0.0279	28.534	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	12	0.028	31.128	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	13	0.028	33.722	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	14	0.028	36.316	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	15	0.028	38.91	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	16	0.0279	41.504	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	17	0.028	44.098	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	18	0.028	46.692	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	19	0.0279	49.286	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	20	0.0279	51.88	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	21	0.028	54.474	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	

	22	0.028	57.068	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	23	0.028	59.662	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	24	0.028	62.256	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	25	0.028	64.85	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	26	0.028	67.444	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666	
	27	0.028	70.038	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	28	0.028	72.632	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	29	0.028	75.226	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	30	0.028	77.82	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	31	0.028	80.414	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	32	0.028	83.008	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	33	0.028	85.602	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	34	0.028	88.196	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	35	0.028	90.79	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	36	0.0279	93.384	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	37	0.028	95.978	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	38	0.028	98.572	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	39	0.028	101.166	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	40	0.028	103.76	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	41	0.028	106.354	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	42	0.028	108.948	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666	
	43	0.0279	111.542	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	44	0.028	114.136	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	45	0.028	116.73	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	46	0.0279	119.324	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	47	0.0279	121.918	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	48	0.028	124.512	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	49	0.028	127.106	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	50	0.028	129.7	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666	
	51	0.028	132.294	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	52	0.028	134.888	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	53	0.028	137.482	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	54	0.028	140.076	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	55	0.028	142.67	23.82157	23.5666	23.5666	23.5666	23.51711	23.5666	
	56	0.028	145.264	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	57	0.028	147.858	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666	

	58	0.028	150.452	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	59	0.028	153.046	23.82157	23.59134	23.5666	23.5666	23.51711	23.5666	
	60	0.028	155.64	23.82157	23.5666	23.5666	23.59134	23.51711	23.5666	
	61	0.028	158.234	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	62	0.028	160.828	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666	
	63	0.0279	163.422	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666	
	64	0.028	166.016	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666	
	65	0.028	168.61	23.82157	23.59134	23.5666	23.59134	23.51711	23.5666	
	66	0.028	171.204	23.82157	23.59134	23.5666	23.59134	23.51711	23.5666	
	67	0.028	173.798	23.82157	23.59134	23.54185	23.59134	23.5666	23.59134	
	68	0.028	176.392	23.82157	23.59134	23.5666	23.59134	23.54185	23.59134	
	69	0.028	178.986	23.82157	23.51711	23.51711	23.61608	23.46762	23.59134	
	70	0.028	181.58	23.79629	23.59134	23.59134	23.59134	23.5666	23.59134	
	71	0.028	184.174	23.84685	23.59134	23.54185	23.59134	23.5666	23.59134	
	72	0.028	186.768	23.82157	23.59134	23.5666	23.61608	23.5666	23.64082	
	73	0.028	189.362	23.69515	23.22014	23.46762	23.51711	23.5666	23.51711	
	74	0.028	191.956	22.93663	21.6845	22.47737	22.99737	23.39339	23.02212	
	75	0.028	194.55	21.79886	20.27075	21.18866	22.22966	22.97261	22.27921	
	76	0.028	197.144	20.73694	19.20301	20.17147	21.51099	22.6012	21.56056	
	77	0.028	199.738	19.87728	18.38285	19.50109	20.84144	21.83321	20.84144	
	78	0.028	202.332	19.19462	17.88548	19.02909	20.29557	21.28785	20.1963	
	79	0.028	204.926	18.56252	17.33811	18.55688	19.42658	20.69259	19.42658	
	80	0.028	207.52	17.90514	16.64106	17.91036	18.2088	20.07218	18.70602	
	81	0.028	210.114	17.32361	15.99339	17.21367	16.93985	19.42658	17.98498	
	82	0.028	212.708	16.76736	15.51985	16.59125	15.91863	18.80543	17.28834	
	83	0.028	215.302	16.31225	15.14585	16.01831	15.29546	18.25853	16.74066	
	84	0.028	217.896	15.95828	14.8715	15.5697	14.8715	17.71135	16.24254	
	85	0.028	220.49	15.6043	14.64699	15.19572	14.62204	17.23856	15.84387	
	86	0.028	223.084	15.27561	14.39747	14.84656	14.44738	16.76557	15.49492	
	87	0.028	225.678	14.89635	14.17286	14.59709	14.3226	16.36709	15.17079	
	88	0.028	228.272	14.64352	13.97316	14.42242	14.22277	16.01831	14.92139	
	89	0.028	230.866	14.34011	13.74846	14.19782	14.09797	15.69433	14.67194	
	90	0.028	233.46	14.11255	13.57366	14.04805	13.99812	15.3952	14.44738	
	91	0.028	236.054	13.85971	13.39883	13.8733	13.89826	15.12091	14.24773	
	92	0.028	238.648	13.60688	13.19899	13.69852	13.72349	14.8715	14.02309	
	93	0.028	241.242	13.37932	12.99911	13.4238	13.37385	14.59709	13.74846	

	94	0.028	243.836	13.15177	12.69923	13.14902	12.92415	14.29765	13.39883	
	95	0.028	246.43	12.89893	12.32426	12.69923	12.47426	14.02309	13.07407	
	96	0.028	249.024	12.6208	11.92415	12.27425	12.07421	13.67355	12.69923	
	97	0.0279	251.618	12.36796	11.57393	11.92415	11.72404	13.34887	12.34926	
	98	0.028	254.212	12.14041	11.34873	11.64899	11.49887	13.04908	12.07421	
	99	0.028	256.806	11.91285	11.19857	11.4238	11.29868	12.77421	11.84911	
	100	0.0278	259.4	11.71058	11.02336	11.19857	11.09846	12.49926	11.59895	
	101	0.0271	261.994	11.50831	10.89819	11.04839	10.94826	12.29926	11.4238	
	102	0.0259	264.588	11.33132	10.74797	10.87316	10.77301	12.0492	11.24863	
	103	0.0249	267.182	11.12905	10.57269	10.72293	10.59773	11.84911	11.07342	
	104	0.024	269.776	10.95207	10.42242	10.54765	10.42242	11.64899	10.89819	
	105	0.0233	272.37	10.80036	10.27214	10.39738	10.27214	11.47385	10.77301	
	106	0.0227	274.964	10.64866	10.14688	10.22204	10.09678	11.32371	10.59773	
	107	0.022	277.558	10.47167	9.996559	10.04667	9.871273	11.12349	10.44747	
	108	0.0215	280.152	10.31997	9.871273	9.896331	9.72091	10.94826	10.29719	
	109	0.0209	282.746	10.19355	9.745972	9.745972	9.545462	10.82309	10.17193	
	110	0.0205	285.34	10.06713	9.620658	9.595593	9.395055	10.69789	10.04667	
	111	0.0201	287.934	9.94071	9.495329	9.445193	9.244627	10.54765	9.921389	
	112	0.0197	290.528	9.814291	9.395055	9.294772	9.069102	10.42242	9.796094	
	113	0.0194	293.122	9.713155	9.2697	9.169406	8.91863	10.27214	9.670785	
	114	0.019	295.716	9.586736	9.169406	9.044025	8.79322	10.14688	9.570528	
	115	0.0188	298.31	9.4856	9.044025	8.893549	8.64271	9.996559	9.445193	
	116	0.0185	300.904	9.384464	8.91863	8.743053	8.492179	9.871273	9.319844	
	117	0.0182	303.498	9.283329	8.79322	8.617623	8.341627	9.745972	9.19448	
	118	0.018	306.092	9.182193	8.692882	8.492179	8.241248	9.620658	9.094179	
	119	0.0177	308.686	9.081058	8.567447	8.366721	8.115761	9.495329	8.96879	
	120	0.0175	311.28	8.979922	8.441997	8.216152	7.965157	9.369985	8.868468	
	121	0.0173	313.874	8.878786	8.316533	8.065562	7.839639	9.219554	8.743053	
	122	0.017	316.468	8.777651	8.191055	7.965157	7.714106	9.119255	8.64271	
	123	0.0168	319.062	8.676515	8.090662	7.864744	7.613669	9.018947	8.542358	
	124	0.0165	321.656	8.600663	7.965157	7.714106	7.48811	8.893549	8.416906	
	125	0.0163	324.25	8.474244	7.839639	7.613669	7.387652	8.768137	8.316533	
	126	0.016	326.844	8.373108	7.714106	7.48811	7.262068	8.667796	8.241248	
	127	0.0158	329.438	8.297257	7.613669	7.387652	7.161589	8.567447	8.115761	
	128	0.0156	332.032	8.196121	7.48811	7.287186	7.061102	8.467088	8.015361	
	129	0.0155	334.626	8.094985	7.387652	7.161589	6.960606	8.366721	7.914952	

	130	0.0153	337.22	7.99385	7.262068	7.061102	6.8601	8.241248	7.814533	
	131	0.0151	339.814	7.892714	7.161589	6.960606	6.759585	8.140859	7.739213	
	132	0.0149	342.408	7.791579	7.061102	6.8601	6.659061	8.065562	7.638779	
	133	0.0148	345.002	7.715727	6.960606	6.759585	6.583662	7.965157	7.563447	
	134	0.0146	347.596	7.614591	6.8601	6.684193	6.508257	7.864744	7.462996	
	135	0.0145	350.19	7.513456	6.759585	6.583662	6.40771	7.789427	7.362537	
	136	0.0143	352.784	7.41232	6.659061	6.483121	6.307154	7.688997	7.287186	
	137	0.0142	355.378	7.336468	6.583662	6.40771	6.23173	7.588558	7.18671	
	138	0.0141	357.972	7.235333	6.483121	6.332294	6.156302	7.513223	7.111347	
	139	0.014	360.566	7.134197	6.40771	6.23173	6.080868	7.412768	7.035979	
	140	0.0138	363.16	7.033062	6.307154	6.156302	6.00543	7.33742	6.960606	
	141	0.0137	365.754	6.95721	6.23173	6.080868	5.904837	7.262068	6.885227	
	142	0.0136	368.348	6.856074	6.131158	5.980282	5.829386	7.18671	6.784714	
	143	0.0135	370.942	6.780223	6.030576	5.904837	5.75393	7.111347	6.709324	
	144	0.0134	373.536	6.679087	5.955134	5.829386	5.678468	7.035979	6.633928	
	145	0.0133	376.13	6.603235	5.879687	5.75393	5.628158	6.960606	6.558527	
	146	0.0132	378.724	6.5021	5.804234	5.678468	5.552688	6.885227	6.483121	
	147	0.0131	381.318	6.426248	5.728776	5.628158	5.477213	6.809843	6.40771	
	148	0.013	383.912	6.350396	5.678468	5.552688	5.426894	6.709324	6.332294	
	149	0.0129	386.506	6.274545	5.577845	5.477213	5.35141	6.659061	6.256872	
	150	0.0128	389.1	6.173409	5.502372	5.401733	5.275921	6.558527	6.181445	
	151	0.0127	391.694	6.097557	5.452054	5.326248	5.225593	6.508257	6.131158	
	152	0.0126	394.288	5.996422	5.376572	5.275921	5.175262	6.432848	6.055723	
	153	0.0125	396.882	5.945854	5.301085	5.200427	5.099761	6.357433	5.980282	
	154	0.0124	399.476	5.870002	5.250757	5.150095	5.049424	6.307154	5.929986	
	155	0.0123	402.07	5.794151	5.175262	5.099761	4.999085	6.256872	5.854537	
	156	0.0122	404.664	5.743583	5.124928	5.049424	4.948743	6.181445	5.804234	
	157	0.0121	407.258	5.667731	5.074593	4.999085	4.8984	6.131158	5.75393	
	158	0.012	409.852	5.591879	5.024255	4.923572	4.848054	6.080868	5.703623	
	159	0.0119	412.446	5.541312	4.948743	4.873227	4.797706	6.00543	5.653314	
	160	0.0118	415.04	5.46546	4.8984	4.82288	4.747355	5.955134	5.577845	
	161	0.0117	417.634	5.414892	4.848054	4.772531	4.671825	5.904837	5.52753	
	162	0.0116	420.228	5.33904	4.797706	4.722179	4.646647	5.854537	5.477213	
	163	0.0116	422.822	5.288473	4.747355	4.671825	4.596289	5.779082	5.401733	
	164	0.0115	425.416	5.237905	4.697002	4.621468	4.54593	5.728776	5.35141	
	165	0.0114	428.01	5.162053	4.646647	4.57111	4.495568	5.678468	5.301085	

	166	0.0113	430.604	5.111485	4.596289	4.520749	4.445203	5.628158	5.250757	
	167	0.0112	433.198	5.060917	4.54593	4.470386	4.42002	5.577845	5.200427	
	168	0.0111	435.792	5.01035	4.495568	4.42002	4.369652	5.52753	5.150095	
	169	0.011	438.386	4.934498	4.42002	4.369652	4.319282	5.477213	5.099761	
	170	0.0109	440.98	4.88393	4.394837	4.319282	4.26891	5.426894	5.049424	
	171	0.0108	443.574	4.833362	4.344468	4.294096	4.218535	5.401733	4.999085	
	172	0.0107	446.168	4.782795	4.294096	4.243723	4.193347	5.35141	4.973914	
	173	0.0106	448.762	4.732227	4.26891	4.218535	4.142969	5.301085	4.923572	
	174	0.0106	451.356	4.681659	4.218535	4.168158	4.117779	5.250757	4.873227	
	175	0.0105	453.95	4.656375	4.168158	4.117779	4.067397	5.200427	4.82288	
	176	0.0104	456.544	4.605807	4.142969	4.092588	4.042206	5.175262	4.772531	
	177	0.0103	459.138	4.555239	4.092588	4.042206	3.991821	5.124928	4.747355	
	178	0.0102	461.732	4.504672	4.067397	4.017013	3.966627	5.074593	4.697002	
	179	0.0101	464.326	4.479388	4.017013	3.966627	3.916239	5.024255	4.646647	
	180	0.0101	466.92	4.403536	3.966627	3.941433	3.891044	4.999085	4.596289	
	181	0.01	469.514	4.378252	3.941433	3.891044	3.840652	4.948743	4.57111	
	182	0.0099	472.108	4.327684	3.891044	3.865848	3.815455	4.923572	4.520749	
	183	0.0099	474.702	4.3024	3.865848	3.815455	3.765059	4.873227	4.470386	
	184	0.0098	477.296	4.251833	3.815455	3.790257	3.739861	4.82288	4.445203	
	185	0.0097	479.89	4.226549	3.790257	3.739861	3.714662	4.797706	4.42002	
	186	0.0097	482.484	4.175981	3.765059	3.714662	3.689462	4.747355	4.369652	
	187	0.0096	485.078	4.150697	3.714662	3.689462	3.664262	4.722179	4.344468	
	188	0.0095	487.672	4.100129	3.689462	3.664262	3.613859	4.697002	4.319282	
	189	0.0095	490.266	4.074845	3.664262	3.639061	3.588657	4.671825	4.26891	
	190	0.0094	492.86	4.024278	3.639061	3.588657	3,563455	4.621468	4.243723	
	191	0.0094	495.454	3.998994	3.613859	3.588657	3.538252	4.596289	4.218535	
	192	0.0093	498.048	3.97371	3.588657	3.538252	3.513048	4.57111	4.193347	
	193	0.0093	500.642	3.948426	3.563455	3.513048	3.487844	4.54593	4.142969	
	194	0.0092	503.236	3.923142	3.513048	3.487844	3.462639	4.520749	4.142969	
	195	0.0091	505.83	3.872574	3.513048	3.462639	3.437433	4.470386	4.092588	
	196	0.0091	508.424	3.84729	3.462639	3.437433	3.412227	4.445203	4.067397	
	197	0.009	511.018	3.822006	3.437433	3.412227	3.387021	4.42002	4.042206	
	198	0.009	513.612	3.796722	3.412227	3.387021	3.361813	4.394837	4.017013	
	199	0.0089	516.206	3.771439	3.387021	3.361813	3.336606	4.369652	3.991821	
	200	0.0089	518.8	3.720871	3.361813	3.336606	3.311397	4.344468	3.941433	
	201	0.0088	521.394	3.695587	3.336606	3.311397	3.286188	4.319282	3.916239	

	202	0.0088	523.988	3.670303	3.311397	3.286188	3.260979	4.26891	3.916239	
	203	0.0087	526.582	3.645019	3.286188	3.260979	3.235769	4.26891	3.865848	
	204	0.0087	529.176	3.619735	3.260979	3.235769	3.210558	4.218535	3.840652	
	205	0.0086	531.77	3.594451	3.235769	3.210558	3.185347	4.218535	3.815455	
	206	0.0086	534.364	3.569167	3.210558	3.185347	3.160135	4.193347	3.790257	
	207	0.0085	536.958	3.543883	3.185347	3.160135	3.134923	4.168158	3.765059	
	208	0.0085	539.552	3.5186	3.160135	3.134923	3.134923	4.142969	3.739861	
	209	0.0085	542.146	3.493316	3.134923	3.134923	3.10971	4.117779	3.714662	
	210	0.0084	544.74	3.468032	3.134923	3.084496	3.084496	4.092588	3.689462	
	211	0.0084	547.334	3.442748	3.10971	3.084496	3.059282	4.067397	3.689462	
	212	0.0084	549.928	3.417464	3.084496	3.059282	3.034068	4.042206	3.664262	
	213	0.0083	552.522	3.39218	3.059282	3.034068	3.008853	4.017013	3.639061	
	214	0.0083	555.116	3.366896	3.034068	3.008853	2.983637	3.991821	3.588657	
	215	0.0082	557.71	3.341612	3.034068	2.983637	2.983637	3.966627	3.588657	
	216	0.0082	560.304	3.316328	2.983637	2.983637	2.95842	3.941433	3.563455	
	217	0.0082	562.898	3.291044	2.983637	2.95842	2.933203	3.916239	3.538252	
	218	0.0081	565.492	3.265761	2.95842	2.933203	2.933203	3.891044	3.513048	
	219	0.0081	568.086	3.265761	2.933203	2.907986	2.907986	3.891044	3.487844	
	220	0.0081	570.68	3.240477	2.907986	2.882768	2.882768	3.865848	3.462639	
	221	0.008	573.274	3.215193	2.907986	2.882768	2.882768	3.840652	3.462639	
	222	0.008	575.868	3.189909	2.882768	2.857549	2.857549	3.815455	3.437433	
	223	0.008	578.462	3.189909	2.857549	2.857549	2.857549	3.790257	3.412227	
	224	0.008	581.056	3.164625	2.857549	2.83233	2.83233	3.790257	3.412227	
	225	0.0079	583.65	3.139341	2.83233	2.80711	2.80711	3.765059	3.387021	
	226	0.0079	586.244	3.114057	2.80711	2.78189	2.80711	3.739861	3.361813	
	227	0.0079	588.838	3.114057	2.80711	2.78189	2.78189	3.739861	3.336606	
	228	0.0078	591.432	3.088773	2.78189	2.756669	2.756669	3.714662	3.311397	
	229	0.0078	594.026	3.063489	2.756669	2.731447	2.731447	3.689462	3.311397	
	230	0.0078	596.62	3.038205	2.756669	2.731447	2.731447	3.664262	3.286188	
	231	0.0078	599.214	3.038205	2.731447	2.706225	2.706225	3.664262	3.260979	
	232	0.0077	601.808	3.012922	2.731447	2.706225	2.706225	3.639061	3.260979	
	233	0.0077	604.402	3.012922	2.706225	2.681002	2.681002	3.613859	3.235769	
	234	0.0077	606.996	2.987638	2.681002	2.681002	2.681002	3.613859	3.210558	
	235	0.0076	609.59	2.962354	2.681002	2.655779	2.655779	3.613859	3.210558	
	236	0.0076	612.184	2.962354	2.655779	2.655779	2.655779	3.588657	3.185347	
	237	0.0076	614.778	2.93707	2.655779	2.630555	2.630555	3.563455	3.185347	

	238	0.0076	617.372	2.911786	2.630555	2.630555	2.630555	3.563455	3.160135	
	239	0.0075	619.966	2.911786	2.630555	2.605331	2.605331	3.538252	3.160135	
	240	0.0075	622.56	2.886502	2.605331	2.605331	2.605331	3.513048	3.134923	
	241	0.0075	625.154	2.886502	2.605331	2.580106	2.580106	3.513048	3.10971	
	242	0.0075	627.748	2.861218	2.580106	2.55488	2.580106	3.487844	3.10971	
	243	0.0075	630.342	2.861218	2.580106	2.55488	2.55488	3.487844	3.10971	
	244	0.0074	632.936	2.835934	2.55488	2.55488	2.55488	3.462639	3.084496	
	245	0.0074	635.53	2.81065	2.55488	2.529654	2.55488	3.462639	3.084496	
	246	0.0074	638.124	2.81065	2.529654	2.514518	2.529654	3.437433	3.059282	
	247	0.0074	640.718	2.81065	2.529654	2.511995	2.519563	3.437433	3.059282	
	248	0.0074	643.312	2.785366	2.517041	2.501905	2.50695	3.412227	3.034068	
	249	0.0073	645.906	2.785366	2.504427	2.489291	2.494336	3.412227	3.034068	
	250	0.0073	648.5	2.760083	2.496859	2.471632	2.489291	3.412227	3.008853	
	251	0.0073	651.094	2.760083	2.481723	2.461541	2.476677	3.387021	3.008853	
	252	0.0073	653.688	2.734799	2.471632	2.456495	2.466586	3.387021	2.983637	
	253	0.0073	656.282	2.734799	2.466586	2.443881	2.456495	3.361813	2.983637	
	254	0.0072	658.876	2.709515	2.456495	2.433789	2.448927	3.361813	2.95842	
	255	0.0072	661.47	2.709515	2.441358	2.428744	2.436312	3.336606	2.95842	
	256	0.0072	664.064	2.684231	2.433789	2.408561	2.431267	3.336606	2.933203	
	257	0.0072	666.658	2.684231	2.421175	2.398469	2.418652	3.336606	2.933203	
	258	0.0072	669.252	2.684231	2.418652	2.393423	2.413606	3.311397	2.933203	
	259	0.0071	671.846	2.658947	2.408561	2.380808	2.400992	3.311397	2.907986	
	260	0.0071	674.44	2.658947	2.400992	2.378285	2.395946	3.286188	2.907986	
	261	0.0071	677.034	2.633663	2.385854	2.368193	2.380808	3.286188	2.907986	
	262	0.0071	679.628	2.633663	2.375762	2.360624	2.378285	3.286188	2.882768	
	263	0.0071	682.222	2.633663	2.373239	2.348009	2.36567	3.260979	2.882768	
	264	0.0071	684.816	2.608379	2.363147	2.345486	2.358101	3.260979	2.857549	
	265	0.0071	687.41	2.608379	2.353055	2.33287	2.350532	3.235769	2.857549	
	266	0.007	690.004	2.608379	2.348009	2.325301	2.342963	3.235769	2.857549	
	267	0.007	692.598	2.583095	2.337917	2.315209	2.335393	3.235769	2.83233	
	268	0.007	695.192	2.583095	2.330347	2.307639	2.327824	3.210558	2.83233	
	269	0.007	697.786	2.583095	2.322778	2.305116	2.325301	3.210558	2.83233	
	270	0.007	700.38	2.557811	2.310162	2.2925	2.315209	3.210558	2.80711	
	271	0.007	702.974	2.557811	2.305116	2.279884	2.310162	3.185347	2.80711	
	272	0.007	705.568	2.532527	2.302593	2.277361	2.297547	3.185347	2.80711	
	273	0.0069	708.162	2.532527	2.295023	2.269791	2.295023	3.185347	2.78189	

	274	0.0069	710.756	2.532527	2.287454	2.267268	2.284931	3.160135	2.78189	
	275	0.0069	713.35	2.522414	2.272315	2.252129	2.277361	3.160135	2.78189	
	276	0.0069	715.944	2.517357	2.269791	2.242035	2.269791	3.160135	2.756669	
	277	0.0069	718.538	2.507244	2.259698	2.242035	2.262222	3.134923	2.756669	
	278	0.0069	721.132	2.504715	2.252129	2.231942	2.259698	3.134923	2.756669	
	279	0.0069	723.726	2.494602	2.247082	2.221849	2.249605	3.134923	2.756669	
	280	0.0069	726.32	2.487016	2.242035	2.224372	2.249605	3.10971	2.731447	
	281	0.0068	728.914	2.48196	2.236989	2.219325	2.236989	3.10971	2.731447	
	282	0.0068	731.508	2.469318	2.229419	2.201662	2.229419	3.10971	2.731447	
	283	0.0068	734.102	2.461733	2.224372	2.204185	2.229419	3.10971	2.706225	
	284	0.0068	736.696	2.459204	2.219325	2.196615	2.226895	3.10971	2.706225	
	285	0.0068	739.29	2.454147	2.214279	2.191568	2.214279	3.084496	2.706225	
	286	0.0068	741.884	2.446562	2.206709	2.183998	2.206709	3.084496	2.706225	
	287	0.0068	744.478	2.441505	2.201662	2.176428	2.204185	3.084496	2.681002	
	288	0.0068	747.072	2.436449	2.194092	2.171381	2.199138	3.059282	2.681002	
	289	0.0068	749.666	2.43392	2.189045	2.16381	2.194092	3.059282	2.681002	
	290	0.0068	752.26	2.421278	2.186521	2.158763	2.183998	3.059282	2.681002	
	291	0.0067	754.854	2.41875	2.181475	2.15624	2.183998	3.034068	2.655779	
	292	0.0067	757.448	2.413693	2.173904	2.148669	2.176428	3.034068	2.655779	
	293	0.0067	760.042	2.40358	2.173904	2.146146	2.173904	3.034068	2.655779	
	294	0.0067	762.636	2.40358	2.166334	2.143622	2.16381	3.034068	2.655779	
	295	0.0067	765.23	2.398523	2.158763	2.133528	2.166334	3.034068	2.630555	
	296	0.0067	767.824	2.395994	2.15624	2.125958	2.153716	3.008853	2.630555	
	297	0.0067	770.418	2.383352	2.15624	2.131005	2.15624	3.008853	2.630555	
	298	0.0067	773.012	2.378296	2.151193	2.123434	2.153716	3.008853	2.630555	
	299	0.0067	775.606	2.380824	2.146146	2.115863	2.146146	3.008853	2.630555	
	300	0.0067	778.2	2.373239	2.136052	2.105769	2.138575	3.008853	2.605331	
	301	0.0067	780.794	2.37071	2.133528	2.108292	2.136052	2.983637	2.630555	
	302	0.0067	783.388	2.363125	2.125958	2.100722	2.133528	2.983637	2.605331	
	303	0.0066	785.982	2.35554	2.125958	2.095674	2.125958	2.983637	2.605331	
	304	0.0066	788.576	2.353012	2.12091	2.095674	2.125958	2.983637	2.605331	
	305	0.0066	791.17	2.350483	2.118387	2.08558	2.123434	2.983637	2.605331	
	306	0.0066	793.764	2.347955	2.11334	2.088103	2.11334	2.983637	2.605331	
	307	0.0066	796.358	2.337841	2.110816	2.088103	2.110816	2.983637	2.580106	
	308	0.0066	798.952	2.34037	2.108292	2.08558	2.110816	2.95842	2.580106	
	309	0.0066	801.546	2.34037	2.100722	2.080533	2.108292	2.95842	2.580106	

	310	0.0066	804.14	2.332785	2.105769	2.078009	2.105769	2.95842	2.580106	
	311	0.0066	806.734	2.327728	2.103245	2.067914	2.095674	2.95842	2.580106	
	312	0.0066	809.328	2.322671	2.100722	2.070438	2.090627	2.95842	2.580106	
	313	0.0066	811.922	2.327728	2.095674	2.062867	2.098198	2.95842	2.580106	
	314	0.0066	814.516	2.325199	2.098198	2.060343	2.090627	2.95842	2.580106	
	315	0.0066	817.11	2.325199	2.090627	2.06539	2.088103	2.95842	2.55488	
	316	0.0066	819.704	2.312558	2.093151	2.060343	2.08558	2.933203	2.55488	
	317	0.0066	822.298	2.315086	2.088103	2.055296	2.08558	2.933203	2.55488	
	318	0.0066	824.892	2.310029	2.08558	2.055296	2.083056	2.933203	2.55488	
	319	0.0065	827.486	2.307501	2.083056	2.052772	2.078009	2.933203	2.55488	
	320	0.0065	830.08	2.304972	2.080533	2.047724	2.075485	2.933203	2.580106	
	321	0.0065	832.674	2.302444	2.072961	2.045201	2.070438	2.95842	2.580106	
	322	0.0065	835.268	2.297387	2.072961	2.045201	2.078009	2.983637	2.580106	
	323	0.0065	837.862	2.29233	2.070438	2.040153	2.072961	3.008853	2.580106	
	324	0.0065	840.456	2.289802	2.067914	2.037629	2.072961	3.034068	2.580106	
	325	0.0065	843.05	2.29233	2.06539	2.035106	2.070438	3.008853	2.580106	
	326	0.0065	845.644	2.289802	2.060343	2.030058	2.067914	3.008853	2.580106	
	327	0.0065	848.238	2.282217	2.062867	2.032582	2.070438	3.034068	2.580106	
	328	0.0065	850.832	2.27716	2.060343	2.030058	2.070438	3.059282	2.605331	
	329	0.0065	853.426	2.274632	2.060343	2.027534	2.072961	3.084496	2.605331	
	330	0.0065	856.02	2.269575	2.055296	2.032582	2.078009	3.10971	2.605331	
	331	0.0065	858.614	2.272103	2.052772	2.027534	2.067914	3.10971	2.605331	
	332	0.0065	861.208	2.269575	2.045201	2.02501	2.06539	3.10971	2.605331	
	333	0.0065	863.802	2.269575	2.047724	2.027534	2.070438	3.134923	2.605331	
	334	0.0065	866.396	2.264518	2.042677	2.02501	2.067914	3.134923	2.605331	
	335	0.0065	868.99	2.26199	2.045201	2.017439	2.067914	3.134923	2.605331	
	336	0.0065	871.584	2.26199	2.042677	2.014915	2.067914	3.134923	2.605331	
	337	0.0065	874.178	2.26199	2.037629	2.012391	2.055296	3.10971	2.580106	
	338	0.0065	876.772	2.256933	2.040153	2.009868	2.052772	3.084496	2.580106	
	339	0.0065	879.366	2.256933	2.035106	2.014915	2.052772	3.059282	2.55488	
	340	0.0065	881.96	2.251876	2.037629	2.014915	2.050248	3.059282	2.55488	
	341	0.0065	884.554	2.249348	2.030058	2.00482	2.045201	3.034068	2.529654	
	342	0.0065	887.148	2.246819	2.032582	2.00482	2.042677	3.008853	2.529654	
	343	0.0064	889.742	2.244291	2.027534	2.00482	2.050248	2.983637	2.529654	
	344	0.0064	892.336	2.251876	2.027534	2.002296	2.042677	3.008853	2.55488	
	345	0.0064	894.93	2.246819	2.02501	2.002296	2.052772	3.034068	2.580106	

	346	0.0064	897.524	2.239234	2.022487	1.999772	2.047724	3.059282	2.55488	
	347	0.0064	900.118	2.244291	2.022487	1.992201	2.040153	3.059282	2.55488	
	348	0.0064	902.712	2.239234	2.019963	1.994725	2.047724	3.034068	2.55488	
	349	0.0064	905.306	2.236706	2.019963	1.997248	2.035106	3.008853	2.529654	
	350	0.0064	907.9	2.234177	2.014915	1.987153	2.032582	3.008853	2.522086	
	351	0.0064	910.494	2.234177	2.019963	1.989677	2.02501	2.983637	2.517041	
	352	0.0064	913.088	2.231649	2.014915	1.984629	2.02501	2.95842	2.509473	
	353	0.0064	915.682	2.231649	2.017439	1.984629	2.02501	2.95842	2.501905	
	354	0.0064	918.276	2.229121	2.007344	1.979581	2.017439	2.933203	2.499382	
	355	0.0064	920.87	2.224064	2.009868	1.982105	2.017439	2.933203	2.491814	
	356	0.0064	923.464	2.224064	2.00482	1.974533	2.012391	2.933203	2.489291	
	357	0.0064	926.058	2.226592	2.002296	1.969486	2.002296	2.907986	2.489291	
	358	0.0064	928.652	2.221535	1.999772	1.966962	2.00482	2.907986	2.4792	
	359	0.0064	931.246	2.221535	2.00482	1.966962	2.00482	2.907986	2.4792	
	360	0.0064	933.84	2.226592	1.999772	1.966962	2.007344	2.907986	2.471632	
	361	0.0064	936.434	2.219007	2.002296	1.966962	2.002296	2.882768	2.469109	
	362	0.0064	939.028	2.216479	1.999772	1.964438	1.997248	2.882768	2.469109	
	363	0.0064	941.622	2.211422	1.992201	1.95939	1.999772	2.882768	2.466586	
	364	0.0064	944.216	2.21395	1.994725	1.961914	1.994725	2.882768	2.469109	
	365	0.0064	946.81	2.21395	1.989677	1.95939	1.992201	2.882768	2.461541	
	366	0.0064	949.404	2.211422	1.987153	1.954342	1.994725	2.882768	2.459018	
	367	0.0064	951.998	2.208894	1.992201	1.954342	1.992201	2.857549	2.461541	
	368	0.0064	954.592	2.208894	1.987153	1.951818	1.992201	2.857549	2.461541	
	369	0.0064	957.186	2.203837	1.987153	1.951818	1.987153	2.857549	2.453972	
	370	0.0064	959.78	2.203837	1.982105	1.94677	1.989677	2.857549	2.456495	
	371	0.0064	962.374	2.19878	1.979581	1.944246	1.984629	2.857549	2.448927	
	372	0.0064	964.968	2.19878	1.984629	1.949294	1.987153	2.857549	2.448927	
	373	0.0064	967.562	2.201308	1.977057	1.941722	1.982105	2.857549	2.446404	
	374	0.0064	970.156	2.19878	1.977057	1.939198	1.979581	2.857549	2.448927	
	375	0.0064	972.75	2.19878	1.977057	1.941722	1.982105	2.857549	2.448927	
	376	0.0064	975.344	2.201308	1.974533	1.939198	1.979581	2.857549	2.446404	
	377	0.0064	977.938	2.196252	1.977057	1.94677	1.977057	2.857549	2.443881	
	378	0.0064	980.532	2.191195	1.969486	1.936674	1.979581	2.857549	2.441358	
	379	0.0064	983.126	2.188666	1.966962	1.941722	1.974533	2.83233	2.438835	
	380	0.0064	985.72	2.193723	1.969486	1.93415	1.97201	2.83233	2.438835	
	381	0.0064	988.314	2.191195	1.969486	1.936674	1.966962	2.83233	2.436312	

	382	0.0064	990.908	2.186138	1.974533	1.929102	1.964438	2.83233	2.438835	
	383	0.0064	993.502	2.188666	1.969486	1.929102	1.97201	2.83233	2.428744	
	384	0.0064	996.096	2.18361	1.966962	1.929102	1.966962	2.83233	2.428744	
	385	0.0064	998.69	2.188666	1.966962	1.931626	1.977057	2.80711	2.426221	
	386	0.0064	1001.284	2.18361	1.966962	1.929102	1.97201	2.83233	2.431267	
	387	0.0064	1003.878	2.186138	1.966962	1.924054	1.969486	2.83233	2.428744	
	388	0.0064	1006.472	2.18361	1.966962	1.929102	1.969486	2.83233	2.431267	
	389	0.0063	1009.066	2.186138	1.964438	1.929102	1.969486	2.83233	2.428744	
	390	0.0063	1011.66	2.186138	1.966962	1.93415	1.966962	2.83233	2.421175	
	391	0.0063	1014.254	2.186138	1.964438	1.926578	1.95939	2.83233	2.421175	
	392	0.0063	1016.848	2.176024	1.961914	1.92153	1.954342	2.83233	2.421175	
	393	0.0063	1019.442	2.178553	1.95939	1.924054	1.95939	2.83233	2.421175	
	394	0.0063	1022.036	2.181081	1.95939	1.919006	1.951818	2.80711	2.413606	
	395	0.0063	1024.63	2.178553	1.961914	1.924054	1.956866	2.80711	2.413606	
	396	0.0063	1027.224	2.176024	1.95939	1.92153	1.951818	2.80711	2.413606	
	397	0.0063	1029.818	2.176024	1.95939	1.919006	1.954342	2.80711	2.413606	
	398	0.0063	1032.412	2.181081	1.95939	1.919006	1.956866	2.80711	2.403515	
	399	0.0063	1035.006	2.18361	1.956866	1.919006	1.949294	2.80711	2.413606	
	400	0.0063	1037.6	2.176024	1.956866	1.916482	1.956866	2.83233	2.431267	
	401	0.0063	1040.194	2.173496	1.954342	1.92153	1.95939	2.857549	2.438835	
	402	0.0063	1042.788	2.176024	1.956866	1.919006	1.954342	2.857549	2.433789	
	403	0.0063	1045.382	2.170968	1.956866	1.911434	1.956866	2.857549	2.428744	
	404	0.0063	1047.976	2.168439	1.951818	1.913958	1.954342	2.83233	2.423698	
	405	0.0063	1050.57	2.173496	1.954342	1.913958	1.954342	2.83233	2.421175	
	406	0.0063	1053.164	2.173496	1.954342	1.913958	1.951818	2.83233	2.423698	
	407	0.0063	1055.758	2.170968	1.954342	1.913958	1.94677	2.83233	2.413606	
	408	0.0063	1058.352	2.168439	1.954342	1.90891	1.94677	2.80711	2.408561	
	409	0.0063	1060.946	2.170968	1.954342	1.911434	1.949294	2.80711	2.416129	
	410	0.0063	1063.54	2.170968	1.954342	1.911434	1.956866	2.80711	2.421175	
	411	0.0063	1066.134	2.170968	1.954342	1.911434	1.951818	2.83233	2.421175	
	412	0.0063	1068.728	2.170968	1.951818	1.916482	1.951818	2.83233	2.421175	
	413	0.0063	1071.322	2.168439	1.956866	1.911434	1.956866	2.83233	2.423698	
	414	0.0063	1073.916	2.168439	1.954342	1.911434	1.951818	2.83233	2.421175	
	415	0.0063	1076.51	2.170968	1.956866	1.913958	1.949294	2.83233	2.421175	
	416	0.0063	1079.104	2.170968	1.956866	1.913958	1.954342	2.83233	2.418652	
	417	0.0063	1081.698	2.170968	1.951818	1.906386	1.949294	2.83233	2.416129	

	418	0.0063	1084.292	2.165911	1.949294	1.911434	1.94677	2.83233	2.413606	
	419	0.0063	1086.886	2.170968	1.951818	1.913958	1.944246	2.80711	2.411083	
	420	0.0063	1089.48	2.168439	1.951818	1.906386	1.941722	2.80711	2.411083	
	421	0.0063	1092.074	2.176024	1.94677	1.90891	1.94677	2.80711	2.408561	
	422	0.0063	1094.668	2.165911	1.949294	1.90891	1.94677	2.80711	2.408561	
	423	0.0063	1097.262	2.170968	1.951818	1.90891	1.949294	2.80711	2.408561	
	424	0.0063	1099.856	2.170968	1.954342	1.90891	1.941722	2.80711	2.403515	
	425	0.0063	1102.45	2.165911	1.951818	1.90891	1.941722	2.80711	2.406038	
	426	0.0063	1105.044	2.176024	1.954342	1.911434	1.949294	2.80711	2.403515	
	427	0.0063	1107.638	2.165911	1.951818	1.90891	1.941722	2.80711	2.408561	
	428	0.0063	1110.232	2.170968	1.951818	1.90891	1.949294	2.80711	2.403515	
	429	0.0063	1112.826	2.165911	1.951818	1.90891	1.944246	2.78189	2.403515	
	430	0.0063	1115.42	2.168439	1.951818	1.906386	1.939198	2.80711	2.408561	
	431	0.0063	1118.014	2.163383	1.94677	1.906386	1.94677	2.80711	2.408561	
	432	0.0063	1120.608	2.165911	1.954342	1.90891	1.944246	2.80711	2.406038	
	433	0.0063	1123.202	2.168439	1.949294	1.903862	1.941722	2.78189	2.408561	
	434	0.0063	1125.796	2.165911	1.949294	1.906386	1.941722	2.80711	2.403515	
	435	0.0063	1128.39	2.168439	1.951818	1.901338	1.941722	2.78189	2.406038	
	436	0.0063	1130.984	2.170968	1.951818	1.901338	1.944246	2.78189	2.400992	
	437	0.0063	1133.578	2.163383	1.951818	1.903862	1.94677	2.78189	2.408561	
	438	0.0063	1136.172	2.165911	1.954342	1.901338	1.941722	2.78189	2.406038	
	439	0.0063	1138.766	2.168439	1.951818	1.90891	1.944246	2.78189	2.406038	
	440	0.0063	1141.36	2.170968	1.951818	1.901338	1.941722	2.78189	2.406038	
	441	0.0063	1143.954	2.165911	1.949294	1.901338	1.939198	2.78189	2.411083	
	442	0.0063	1146.548	2.170968	1.954342	1.906386	1.941722	2.78189	2.413606	
	443	0.0063	1149.142	2.168439	1.954342	1.903862	1.944246	2.78189	2.416129	
	444	0.0063	1151.736	2.170968	1.954342	1.906386	1.941722	2.78189	2.408561	
	445	0.0063	1154.33	2.165911	1.954342	1.903862	1.951818	2.78189	2.408561	
	446	0.0063	1156.924	2.165911	1.951818	1.903862	1.944246	2.78189	2.411083	
	447	0.0063	1159.518	2.165911	1.951818	1.906386	1.94677	2.78189	2.408561	
	448	0.0063	1162.112	2.165911	1.951818	1.911434	1.941722	2.78189	2.408561	
	449	0.0063	1164.706	2.165911	1.954342	1.906386	1.944246	2.78189	2.400992	
	450	0.0063	1167.3	2.168439	1.949294	1.90891	1.944246	2.78189	2.406038	
	451	0.0063	1169.894	2.168439	1.951818	1.90891	1.944246	2.78189	2.400992	
	452	0.0063	1172.488	2.168439	1.951818	1.906386	1.941722	2.78189	2.411083	
	453	0.0063	1175.082	2.168439	1.956866	1.906386	1.941722	2.78189	2.406038	

	454	0.0063	1177.676	2.170968	1.956866	1.906386	1.941722	2.78189	2.403515	
	455	0.0063	1180.27	2.176024	1.954342	1.906386	1.94677	2.78189	2.408561	
	456	0.0063	1182.864	2.165911	1.954342	1.90891	1.951818	2.78189	2.406038	
	457	0.0063	1185.458	2.168439	1.956866	1.903862	1.941722	2.78189	2.408561	
	458	0.0063	1188.052	2.170968	1.956866	1.911434	1.94677	2.78189	2.408561	
	459	0.0063	1190.646	2.165911	1.954342	1.90891	1.94677	2.78189	2.411083	
	460	0.0063	1193.24	2.170968	1.954342	1.90891	1.941722	2.78189	2.406038	
	461	0.0063	1195.834	2.170968	1.951818	1.906386	1.944246	2.78189	2.403515	
	462	0.0063	1198.428	2.168439	1.954342	1.90891	1.94677	2.78189	2.406038	
	463	0.0063	1201.022	2.168439	1.951818	1.903862	1.941722	2.78189	2.400992	
	464	0.0063	1203.616	2.170968	1.951818	1.906386	1.939198	2.78189	2.403515	
	465	0.0063	1206.21	2.170968	1.956866	1.906386	1.939198	2.78189	2.411083	
	466	0.0063	1208.804	2.165911	1.956866	1.911434	1.944246	2.78189	2.411083	
	467	0.0063	1211.398	2.176024	1.956866	1.90891	1.939198	2.78189	2.411083	
	468	0.0063	1213.992	2.170968	1.95939	1.90891	1.944246	2.78189	2.411083	
	469	0.0063	1216.586	2.170968	1.954342	1.911434	1.941722	2.78189	2.408561	
	470	0.0063	1219.18	2.170968	1.961914	1.90891	1.944246	2.78189	2.408561	
	471	0.0063	1221.774	2.176024	1.956866	1.90891	1.944246	2.78189	2.408561	
	472	0.0063	1224.368	2.173496	1.95939	1.906386	1.949294	2.78189	2.408561	
	473	0.0063	1226.962	2.181081	1.95939	1.913958	1.944246	2.78189	2.406038	
	474	0.0063	1229.556	2.173496	1.95939	1.903862	1.94677	2.78189	2.408561	
	475	0.0063	1232.15	2.170968	1.961914	1.906386	1.944246	2.78189	2.408561	
	476	0.0063	1234.744	2.181081	1.956866	1.911434	1.944246	2.78189	2.408561	
	477	0.0063	1237.338	2.173496	1.95939	1.913958	1.94677	2.78189	2.408561	
	478	0.0063	1239.932	2.176024	1.95939	1.90891	1.941722	2.78189	2.408561	
	479	0.0063	1242.526	2.176024	1.966962	1.90891	1.94677	2.78189	2.413606	
	480	0.0063	1245.12	2.176024	1.95939	1.906386	1.944246	2.78189	2.408561	
	481	0.0063	1247.714	2.178553	1.961914	1.911434	1.941722	2.78189	2.416129	
	482	0.0063	1250.308	2.178553	1.961914	1.911434	1.944246	2.78189	2.416129	
	483	0.0063	1252.902	2.178553	1.964438	1.916482	1.944246	2.78189	2.413606	
	484	0.0063	1255.496	2.178553	1.964438	1.906386	1.949294	2.78189	2.416129	
	485	0.0063	1258.09	2.181081	1.966962	1.90891	1.94677	2.78189	2.413606	
	486	0.0063	1260.684	2.181081	1.964438	1.919006	1.941722	2.78189	2.413606	
	487	0.0063	1263.278	2.173496	1.964438	1.913958	1.94677	2.78189	2.416129	
	488	0.0063	1265.872	2.178553	1.969486	1.913958	1.954342	2.78189	2.426221	
	489	0.0063	1268.466	2.181081	1.961914	1.913958	1.954342	2.80711	2.426221	

	490	0.0063	1271.06	2.186138	1.964438	1.913958	1.954342	2.80711	2.433789	
	491	0.0063	1273.654	2.181081	1.969486	1.919006	1.954342	2.80711	2.433789	
	492	0.0063	1276.248	2.178553	1.969486	1.913958	1.954342	2.80711	2.428744	
	493	0.0063	1278.842	2.186138	1.969486	1.916482	1.954342	2.80711	2.431267	
	494	0.0063	1281.436	2.188666	1.966962	1.92153	1.951818	2.80711	2.433789	
	495	0.0063	1284.03	2.188666	1.97201	1.913958	1.951818	2.80711	2.426221	
	496	0.0063	1286.624	2.186138	1.97201	1.916482	1.954342	2.80711	2.426221	
	497	0.0063	1289.218	2.186138	1.969486	1.924054	1.956866	2.80711	2.431267	
	498	0.0063	1291.812	2.18361	1.97201	1.919006	1.951818	2.80711	2.433789	
	499	0.0063	1294.406	2.188666	1.974533	1.916482	1.95939	2.80711	2.426221	
	500	0.0063	1297	2.193723	1.97201	1.919006	1.951818	2.80711	2.426221	
	501	0.0063	1299.594	2.191195	1.97201	1.924054	1.954342	2.80711	2.426221	
	502	0.0063	1302.188	2.186138	1.977057	1.92153	1.951818	2.80711	2.426221	
	503	0.0063	1304.782	2.186138	1.97201	1.966962	1.979581	2.80711	2.413606	
	504	0.0063	1307.376	2.186138	1.977057	1.929102	1.951818	2.80711	2.428744	
	505	0.0063	1309.97	2.191195	1.979581	1.931626	1.954342	2.80711	2.428744	
	506	0.0063	1312.564	2.196252	1.977057	1.919006	1.939198	2.80711	2.428744	
	507	0.0063	1315.158	2.193723	1.979581	1.919006	1.931626	2.80711	2.426221	
	508	0.0063	1317.752	2.196252	1.987153	1.913958	1.936674	2.80711	2.423698	
	509	0.0063	1320.346	2.196252	1.982105	1.916482	1.929102	2.80711	2.421175	
	510	0.0063	1322.94	2.19878	1.984629	1.92153	1.936674	2.80711	2.428744	
	511	0.0063	1325.534	2.19878	1.987153	1.924054	1.93415	2.80711	2.426221	
	512	0.0063	1328.128	2.201308	1.989677	1.919006	1.94677	2.80711	2.433789	
	513	0.0063	1330.722	2.203837	1.989677	1.926578	1.944246	2.83233	2.456495	
	514	0.0063	1333.316	2.203837	1.989677	1.919006	1.999772	2.857549	2.484246	
	515	0.0063	1335.91	2.224064	2.012391	2.047724	2.08558	2.95842	2.529654	
	516	0.0063	1338.504	2.219007	2.055296	2.037629	2.115863	3.034068	2.605331	
	517	0.0063	1341.098	2.246819	2.100722	2.067914	2.191568	3.134923	2.681002	
	518	0.0063	1343.692	2.272103	2.146146	2.148669	2.302593	3.235769	2.756669	
	519	0.0063	1346.286	2.304972	2.196615	2.224372	2.428744	3.361813	2.83233	
	520	0.0063	1348.88	2.350483	2.259698	2.30007	2.511995	3.513048	2.933203	
	521	0.0063	1351.474	2.413693	2.34044	2.383331	2.580106	3.639061	3.008853	
	522	0.0063	1354.068	2.487016	2.421175	2.428744	2.630555	3.739861	3.059282	
	523	0.0063	1356.662	2.557811	2.496859	2.491814	2.706225	3.840652	3.134923	
	524	0.0063	1359.256	2.608379	2.55488	2.55488	2.731447	3.916239	3.185347	
	525	0.0063	1361.85	2.658947	2.605331	2.605331	2.80711	3.991821	3.260979	

	526	0.0063	1364.444	2.734799	2.681002	2.681002	2.907986	4.067397	3.361813	
	527	0.0063	1367.038	2.785366	2.731447	2.756669	2.95842	4.168158	3.437433	
	528	0.0063	1369.632	2.81065	2.80711	2.80711	2.983637	4.243723	3.538252	
	529	0.0063	1372.226	2.886502	2.857549	2.857549	3.059282	4.369652	3.639061	
	530	0.0063	1374.82	2.962354	3.059282	2.983637	3.160135	4.470386	3.765059	
	531	0.0063	1377.414	3.164625	3.437433	3.134923	3.286188	4.57111	3.891044	
	532	0.0063	1380.008	3.442748	3.815455	3.412227	3.538252	4.697002	4.092588	
	533	0.0063	1382.602	3.695587	4.017013	3.639061	3.739861	4.848054	4.26891	
	534	0.0063	1385.196	3.897858	4.117779	3.840652	3.916239	4.973914	4.445203	
	535	0.0063	1387.79	4.049561	4.168158	4.017013	4.092588	5.124928	4.57111	
	536	0.0063	1390.384	4.125413	4.243723	4.092588	4.193347	5.275921	4.722179	
	537	0.0063	1392.978	4.201265	4.294096	4.168158	4.319282	5.426894	4.82288	
	538	0.0063	1395.572	4.251833	4.344468	4.319282	4.42002	5.552688	4.8984	
	539	0.0063	1398.166	4.327684	4.394837	4.495568	4.621468	5.653314	4.973914	
	540	0.0063	1400.76	4.403536	4.470386	4.646647	4.772531	5.728776	5.049424	
	541	0.0063	1403.354	4.454104	4.520749	4.747355	4.848054	5.804234	5.099761	
	542	0.0064	1405.948	4.529956	4.57111	4.747355	4.82288	5.854537	5.150095	
	543	0.0064	1408.542	4.555239	4.596289	4.722179	4.848054	5.904837	5.200427	
	544	0.0064	1411.136	4.605807	4.621468	4.772531	4.8984	5.980282	5.275921	
	545	0.0064	1413.73	4.631091	4.671825	4.797706	4.923572	6.030576	5.301085	
	546	0.0064	1416.324	4.681659	4.697002	4.82288	4.923572	6.030576	5.326248	
	547	0.0065	1418.918	4.706943	4.722179	4.848054	4.948743	6.00543	5.326248	
	548	0.0065	1421.512	4.732227	4.747355	4.873227	4.973914	5.955134	5.35141	
	549	0.0066	1424.106	4.782795	4.797706	4.8984	4.973914	5.929986	5.35141	
	550	0.0067	1426.7	4.808078	4.82288	4.923572	4.999085	5.904837	5.376572	
	551	0.0067	1429.294	4.833362	4.848054	4.948743	5.024255	5.879687	5.401733	
	552	0.0068	1431.888	4.88393	4.8984	4.999085	5.074593	5.854537	5.426894	
	553	0.0069	1434.482	4.934498	4.923572	5.024255	5.099761	5.829386	5.426894	
	554	0.0069	1437.076	4.959782	4.973914	5.049424	5.124928	5.804234	5.452054	
	555	0.007	1439.67	5.01035	4.999085	5.099761	5.150095	5.804234	5.477213	
	556	0.007	1442.264	5.035634	5.024255	5.124928	5.200427	5.804234	5.502372	
	557	0.0071	1444.858	5.060917	5.049424	5.175262	5.225593	5.804234	5.52753	
	558	0.0073	1447.452	5.111485	5.099761	5.200427	5.250757	5.804234	5.552688	
	559	0.0076	1450.046	5.136769	5.124928	5.225593	5.275921	5.829386	5.577845	
	560	0.0078	1452.64	5.162053	5.150095	5.250757	5.301085	5.829386	5.603002	
	561	0.008	1455.234	5.187337	5.175262	5.250757	5.326248	5.829386	5.628158	

	562	0.0082	1457.828	5.237905	5.200427	5.301085	5.35141	5.854537	5.653314	
	563	0.0083	1460.422	5.263189	5.250757	5.326248	5.376572	5.854537	5.678468	
	564	0.0083	1463.016	5.288473	5.275921	5.35141	5.401733	5.879687	5.703623	
	565	0.0084	1465.61	5.313756	5.301085	5.401733	5.452054	5.879687	5.728776	
	566	0.0085	1468.204	5.364324	5.326248	5.426894	5.452054	5.904837	5.75393	
	567	0.0085	1470.798	5.389608	5.35141	5.452054	5.502372	5.929986	5.779082	
	568	0.0086	1473.392	5.414892	5.401733	5.477213	5.52753	5.929986	5.804234	
	569	0.0087	1475.986	5.440176	5.426894	5.502372	5.552688	5.955134	5.829386	
	570	0.0087	1478.58	5.46546	5.452054	5.52753	5.577845	5.980282	5.854537	
	571	0.0087	1481.174	5.516028	5.477213	5.552688	5.603002	5.980282	5.879687	
	572	0.0088	1483.768	5.541312	5.502372	5.577845	5.628158	6.00543	5.904837	
	573	0.0088	1486.362	5.566595	5.52753	5.603002	5.653314	6.030576	5.929986	
	574	0.0088	1488.956	5.591879	5.552688	5.628158	5.678468	6.055723	5.955134	
	575	0.0089	1491.55	5.617163	5.603002	5.653314	5.703623	6.080868	5.980282	
	576	0.0089	1494.144	5.642447	5.603002	5.678468	5.728776	6.080868	6.00543	
	577	0.0089	1496.738	5.667731	5.628158	5.703623	5.75393	6.106014	6.030576	
	578	0.009	1499.332	5.693015	5.653314	5.728776	5.779082	6.131158	6.055723	
	579	0.009	1501.926	5.718299	5.678468	5.75393	5.804234	6.156302	6.080868	
	580	0.0091	1504.52	5.743583	5.703623	5.779082	5.829386	6.181445	6.106014	
	581	0.0091	1507.114	5.768867	5.75393	5.804234	5.854537	6.206588	6.131158	
	582	0.0091	1509.708	5.794151	5.779082	5.829386	5.879687	6.23173	6.156302	
	583	0.0092	1512.302	5.844718	5.804234	5.879687	5.929986	6.256872	6.181445	
	584	0.0092	1514.896	5.870002	5.829386	5.904837	5.955134	6.282013	6.206588	
	585	0.0092	1517.49	5.895286	5.854537	5.929986	5.980282	6.307154	6.256872	
	586	0.0093	1520.084	5.92057	5.879687	5.929986	6.00543	6.307154	6.256872	
	587	0.0093	1522.678	5.945854	5.904837	5.980282	6.030576	6.332294	6.282013	
	588	0.0093	1525.272	5.971138	5.929986	6.00543	6.030576	6.357433	6.307154	
	589	0.0094	1527.866	5.996422	5.955134	6.030576	6.080868	6.382572	6.332294	
	590	0.0094	1530.46	6.021706	5.980282	6.055723	6.106014	6.40771	6.357433	
	591	0.0094	1533.054	6.04699	6.00543	6.080868	6.131158	6.432848	6.382572	
	592	0.0095	1535.648	6.072273	6.030576	6.106014	6.156302	6.457985	6.40771	
	593	0.0095	1538.242	6.097557	6.055723	6.131158	6.181445	6.483121	6.432848	
	594	0.0095	1540.836	6.122841	6.080868	6.156302	6.206588	6.508257	6.457985	
	595	0.0096	1543.43	6.148125	6.106014	6.181445	6.23173	6.508257	6.483121	
	596	0.0096	1546.024	6.173409	6.131158	6.23173	6.256872	6.533393	6.508257	
	597	0.0096	1548.618	6.198693	6.156302	6.23173	6.282013	6.583662	6.533393	

	598	0.0096	1551.212	6.223977	6.181445	6.282013	6.332294	6.608795	6.558527	
	599	0.028	1553.806	6.249261	6.206588	6.307154	6.357433	6.633928	6.608795	
	600	0.028	1556.4	6.274545	6.23173	6.332294	6.357433	6.633928	6.608795	
	601	0.0279	1558.994	6.299829	6.256872	6.357433	6.382572	6.659061	6.633928	
	602	0.028	1561.588	6.325112	6.282013	6.382572	6.40771	6.684193	6.659061	
	603	0.0279	1564.182	6.350396	6.307154	6.382572	6.432848	6.709324	6.684193	

Appendix H

Motor Magnet Restraint

During this Delivery Order Professor Campbell taught a senior level design course in engineering. The interest of one of his students, Mr. Daniel DeHaye, was piqued by the problem of shrink fitting thin, metallic, non megnetic tubing over the rotor magnets to prevent them coming loose from the rotor especially during high speed motor operation (where failures have been reported occuring in other designs). Thus Mr. DeHaye pursued an investigation of this problem (albeit the 4 pole design) for his class project.

His final report is presented in this appendix. Only the color figures have been added to his original work to aid in interpretation. The ANSYS system used for this analysis is a dimension limited one resident on a Hewlett Packard machine at UAH. It will be seen that he has solved the problems of not only the stresses and strains but also of including the effects of rotation and the temperature to which it is required to heat the sleeve prior to placing it over the rotor. His results show this is a very feasible approach to magnet retention.

Mr. DeHaye's figure of 15-20% cost of Shuttle refurbishment due to hydraulics is too high. However it is substantial and a NASA effort to cut or eliminate it is actively underway.

Motor Magnet Restraint

ME 465

Final Report

3-12-93

David DeHaye

I. Problem description

This project is part of an effort by the Research Institute (RI) and the University of Alabama in Huntsville (UAH) to design a 3 inch permanent magnet motor. The objectives of my project were to define a methodology for the design of magnet restraints to be used on permanent magnet motors, and to use this methodology to design magnet restraints for the RI/UAH motor. The RI/UAH motor is designed to be used on an electromechanical thrust vector control actuator. The electromechanical system is intended to replace hydraulic systems that can be expensive to maintain. For example, each time a space shuttle is refurbished, 15-20% of the cost comes from the hydraulic systems. Therefore, my project will contribute to a design effort that could save a large amount of money. The magnet restraint is being designed to overcome problems with motors that use magnets that are bonded to the rotor using adhesives. The problem with using a motor that has glued on magnets is that at high rpm the centrifugal forces involved can cause the magnets to break free from the rotor at the bond line. The restraint being designed is a non-magnetic sleeve that will be shrink fitted over the magnets to hold them onto the rotor. By using finite element modeling (FEM), a shrink fit can be designed so that the magnets are always in compression at their bases. This will ensure that the magnets will not break free from the rotor.

II. Design options considered

When I started to work on this project, the method of restraint had already been decided. A non-magnetic sleeve will be shrunk over the magnets to hold them in place. However, the method of performing the design was not specified. There are at least three methods that could have been used to perform the design. It could have been done by hand, but this method might give inaccurate results and it would require that the entire process be

repeated for different motor configurations, such as a larger motor or a different number of magnets. The second method is to write a fill in the blanks computer program. This would be an automation of the process done by hand. The accuracy of the results would be no better, but once the program is written, the analysis could be repeated quickly for different motor configurations. The third method is to use an FEM computer program such as ANSYS. This method should provide accurate results and after the model is first defined, only a few lines of the input file will need to be changed to account for different variables. I chose to use ANSYS to do the design of the motor magnet restraint.

III. Reasons for selection of design method

I chose to do the design of the motor magnet restraint using ANSYS. There are a number of reasons why I chose this design method. I am familiar with the program, and the results are probably more accurate than the results I would get using other methods. Also, different motor configurations can be analyzed by changing a few lines in the input file. Another reason is that the shrink fit is easy to simulate using ANSYS. This is done by using an interface element that can specify an interference fit between two adjacent elements. These reasons lead me to believe that the use of ANSYS is the best method for doing the design.

IV. Design description

A. Design overview

Figure I shows what the cross section of a typical permanent magnet motor looks like. The magnets are glued to the rotor and can break loose at high rpm. This problem is going to be fixed by designing retaining sleeves that will be shrunk over the magnets to hold them onto the rotor. An element plot of the restraint and motor can be seen in figure

2. The bands of thin elements at the outside edge of the circle represent the retaining sleeve. The rest of the elements represent the magnets, the rotor, and the motor shaft.

The design of the retaining sleeve for the 3 inch RI/UAH motor was done using ANSYS. Titanium was used for the sleeve because it is light in weight, relatively stiff, non-magnetic, and has a high yield strength. I found that by using an interference fit of one part in a thousand, and a sleeve thickness of 1 mm, the magnets would stay in compression at their bases at 20,000 rpm. This setup gives a factor of safety of 6.5. This amount of interference will require that the sleeve be heated to about 110°C (200°F) above the temperature of the motor to do the shrink fit. This should be acceptable if the sleeve is always at the same temperature as the motor and magnets. If the temperature of the sleeve should raise above the temperature of the motor, the shrink fit could loosen. If this is a potential problem, the shrink fit could be made with a greater interference so that at operating temperatures it keeps the magnets in compression at their bases. I ran the problem using a 1 mm thick titanium sleeve and the interference that comes from a 210°C (380°F) shrink fit. The factor of safety for this configuration was 3.4. For both of these configurations, the magnets remain in compression at their bases, the factor of safety is good, the sleeve is adequately thin, and the shrink fit temperatures are reasonable. Therefore, a titanium sleeve of 1 mm in thickness should be adequate to retain the magnets on the 3 inch RI/UAH motor. Also, the use of ANSYS as the method for doing the design seemed to be successful.

B. Task descriptions

There were two tasks required to finish this project. The first was to write an input file for ANSYS to do the design of the restraint. The second was to run the program for various motor configurations and analyze the data that was generated by the program.

The input file for ANSYS and a description of the variables that can be modified is shown in appendix A. In writing the input file I encountered mostly minor problems. The biggest problem that I had was in coming up with a way to simulate the interference fit between the sleeve and the motor. I discussed this problem with Dr. Campbell and he called the technical support people at ANSYS. They suggested that an interface element be used. This type of element is used between surfaces that can make and break contact with each other. The attractive feature of this element is that it allows for an interference to be specified between two adjacent elements. By placing these elements between the inside of the retaining sleeve and the outside of the magnets, a shrink fit can be simulated. To see if this type of element could be used to simulate a shrink fit, I tested it on a simple problem. The test problem was a press fit of a ring onto a shaft. The results obtained using ANSYS and the interface element were within five percent of the textbook answer. This convinced me that interface elements could be used to simulate the shrink fit of the restraint over the motor and magnets.

I ran the problem for several motor configurations and analyzed the output. The output is in the form of stress plots and stress tables. For each configuration the first step in analyzing the restraint system was to make sure that the magnets remained in compression at their bases. I did this by looking at the stresses for the nodes on the bases of the magnets. If the stresses in the radial direction are compressive for all of these nodes, then the magnets must be in compression at their bases. A listing of the stresses for the nodes at the base of the magnets in the 3 inch RI/UAH motor is given in appendix B. This listing is for a titanium sleeve that is 1 mm thick and has an interference of one part in a thousand. SX is the stress in the radial direction and the units are in pascals. Once it has been determined that the magnets are in compression at their bases, it is necessary to determine whether the sleeve can tolerate the stresses involved. For each configuration the maximum stress intensity is found by making a plot

of the stress intensity. A stress intensity plot for the 3 inch RI/UAH motor is shown in figure 3. The maximum and minimum stress intensities are marked by an MX and MN on the plot. To the side of the plot, the values for MX and MN are given in pascals. The factor of safety is determined by dividing the yield strength of the sleeve material by MX. In this case, titanium has a yield strength of 830 MPa. Therefore, the safety factor = $\frac{830.0\text{MPa}}{127.8\text{MPa}} = 6.5$, which is acceptable.

This design process was done for several other motor configurations. Some interesting results were obtained by doing this. For a motor that is roughly twice as big in diameter as the RI/UAH motor, the factor of safety using a I mm thick titanium sleeve was found to be 1.75. The interference fit had to be increased to about one part in 250 to keep the magnets in compression at their bases. This made the maximum stress intensity go up and the factor of safety go down. This also means that the sleeve would have to be about 420°C (750°F) above the temperature of the motor to do the shrink fit. These results indicate that the use of a shrink fitted retaining sleeve might be limited to smaller motors. I had one interesting problem in doing the analysis of the RI/UAH motor. The manufacturers data for the magnets gave a modulus of elasticity that was about one thousand times less than that of steel. I thought that this was too low and the company was called to find out whether a mistake had been made. They said that this was the correct value, so I ran the problem using this modulus of elasticity. A stress intensity plot of the motor and restraint showed that it had deformed into an almost square shape. This plot is shown in figure 4. Another call was made to the company and this time they said that the value given was a thousand times too low. This problem took about a week to resolve and it is a good example of why you should always check your data and facts.

C. Design integration

There were several constraints and requirements that had to be satisfied for the successful completion of this project, these are listed below.

1) The material for the sleeve has to be non-magnetic.

2) The sleeve must be as thin as possible so that the air gap of the motor is not affected.

3) The magnets should remain in compression at their bases.

4) The temperature required to perform the shrink fit should be low enough that the magnets will not be adversely affected.

5) The method used for the design should be adaptable to other motor configurations.

6) The RI/UAH motor should be able to withstand speeds up to 20,000 rpm.

D. Design safety

If the retaining sleeve were to fail in service it would cause the electromechanical thrust vector control actuator to stop working. This could result in a scrubbed flight or possibly even the crash of the vehicle that it was used in. In either case, the monetary cost would be very high. If the vehicle crashed, this could cause injuries or death. However, the design will probably go through a great deal of testing before it will ever be used on an actual launch vehicle. Therefore, if the retaining sleeve does fail, the costs will be limited to the cost of a prototype and the cost of testing.

V. Summary

I believe that the two main objectives of this project have been met. The first objective was to define a methodology for the design of magnet restraints to be used on permanent magnet motors. I did this by using ANSYS to do the design. It gives accurate results and it is easy to handle different motor configurations by changing the input file of the program. The second objective was to use this methodology to do a design of a magnet restraint for the 3 inch RI/UAH motor. I used ANSYS to design a restraint for this motor and determined that a I mm thick titanium sleeve will work. Therefore, I think that this project was a success. If I were to do it over again, I would not do it differently, but I could have used more time. With extra time I could have investigated the possibility of using a thinner sleeve.

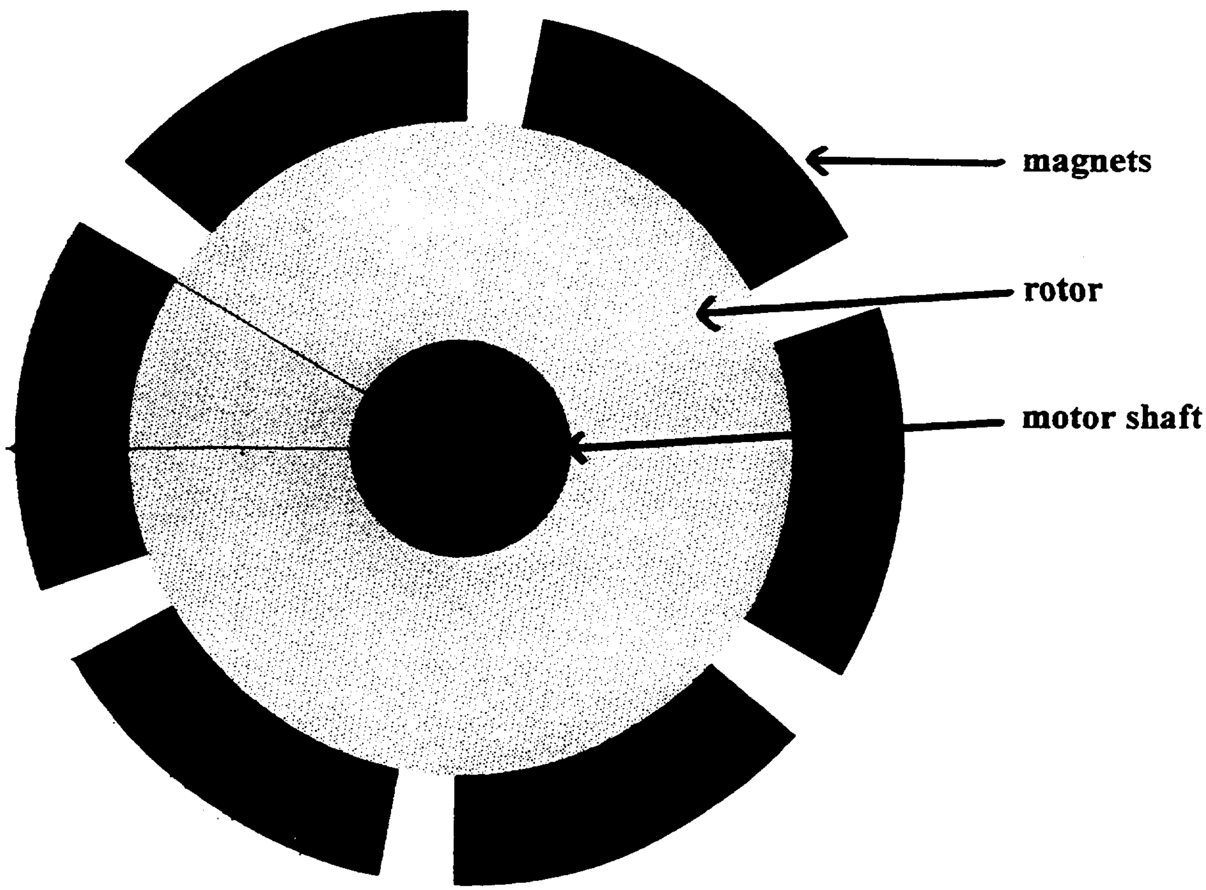
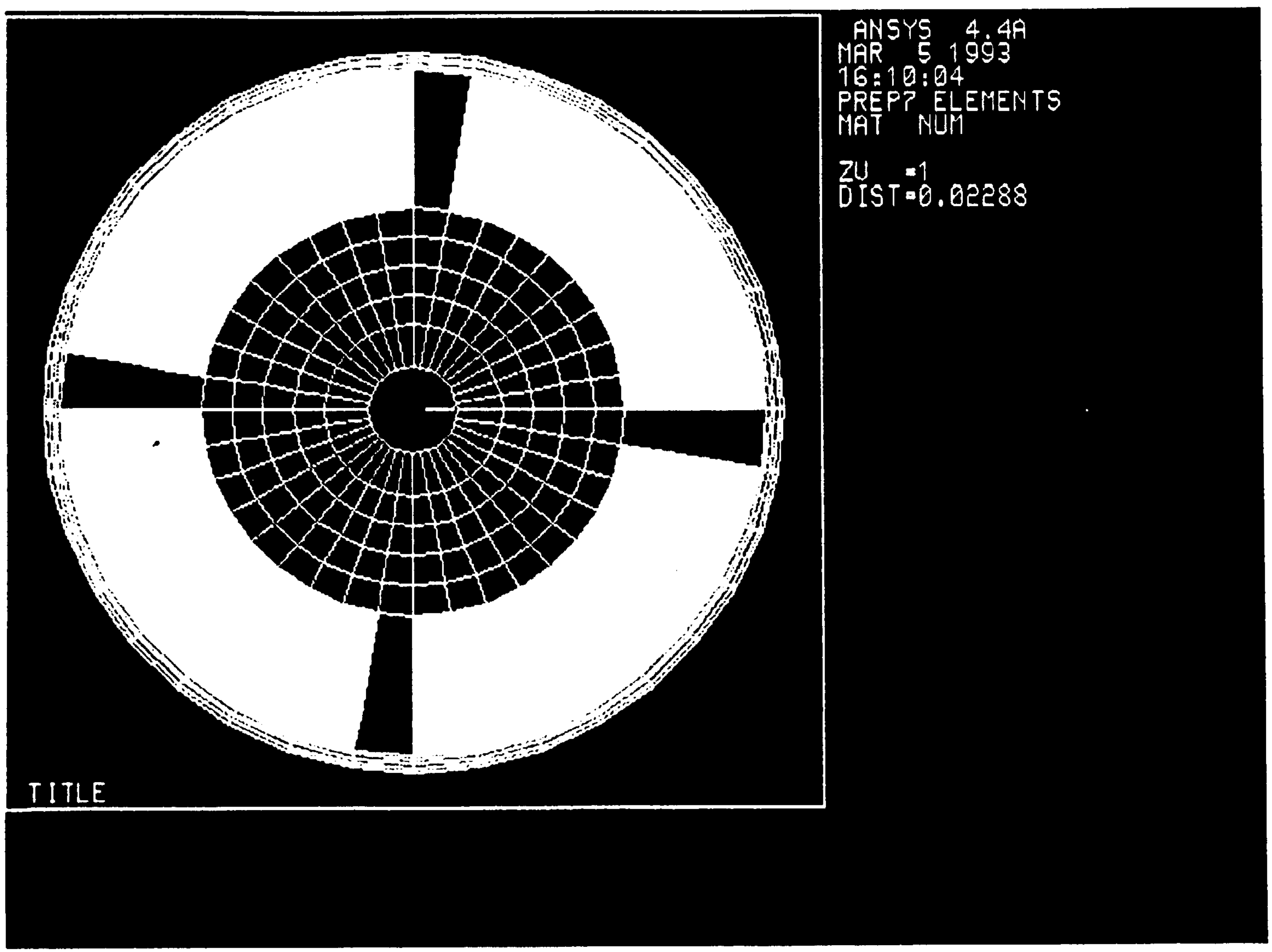


Figure 1.

Motor Cross Section Showing Finite Elements



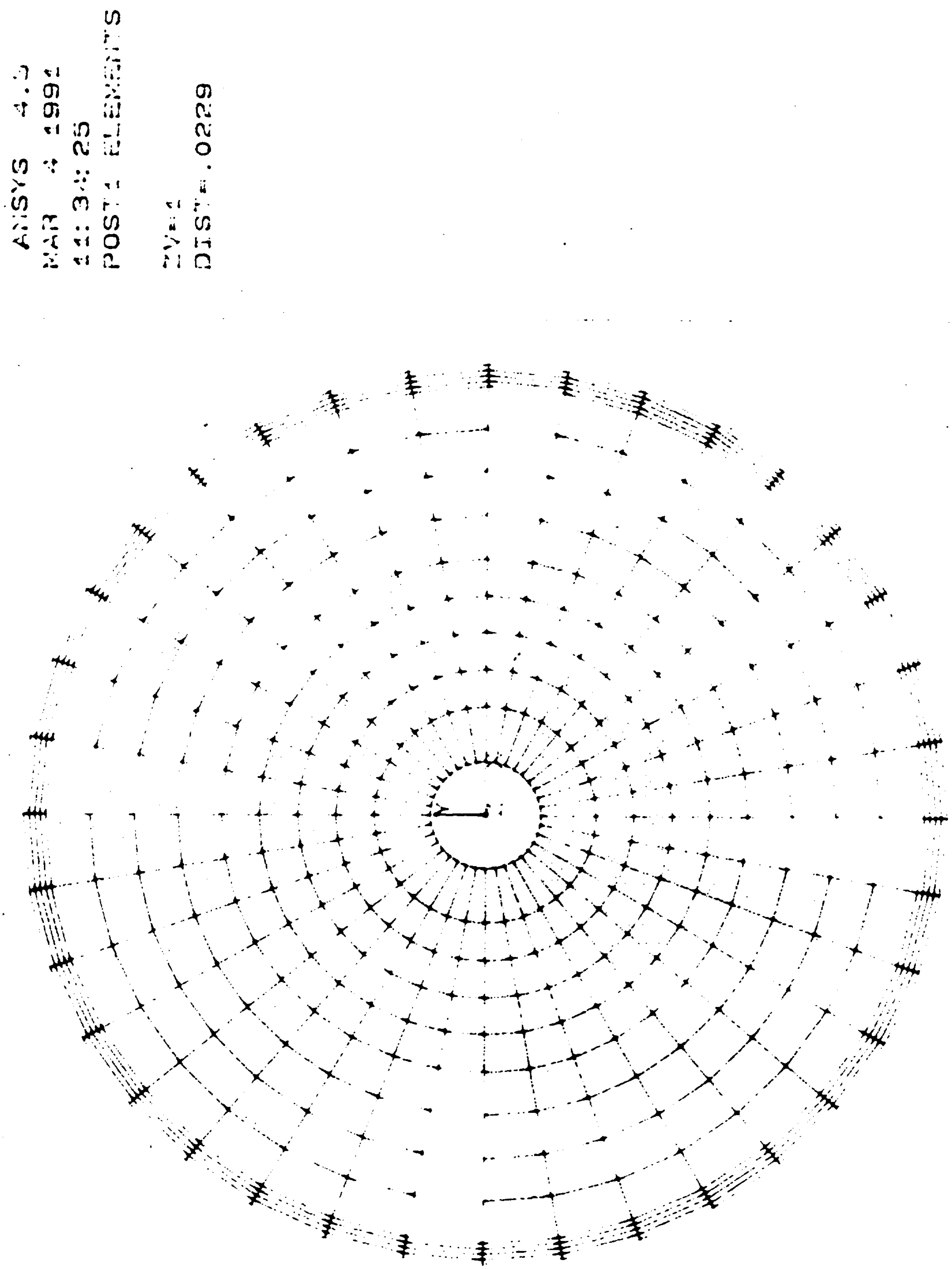


Figure 2.

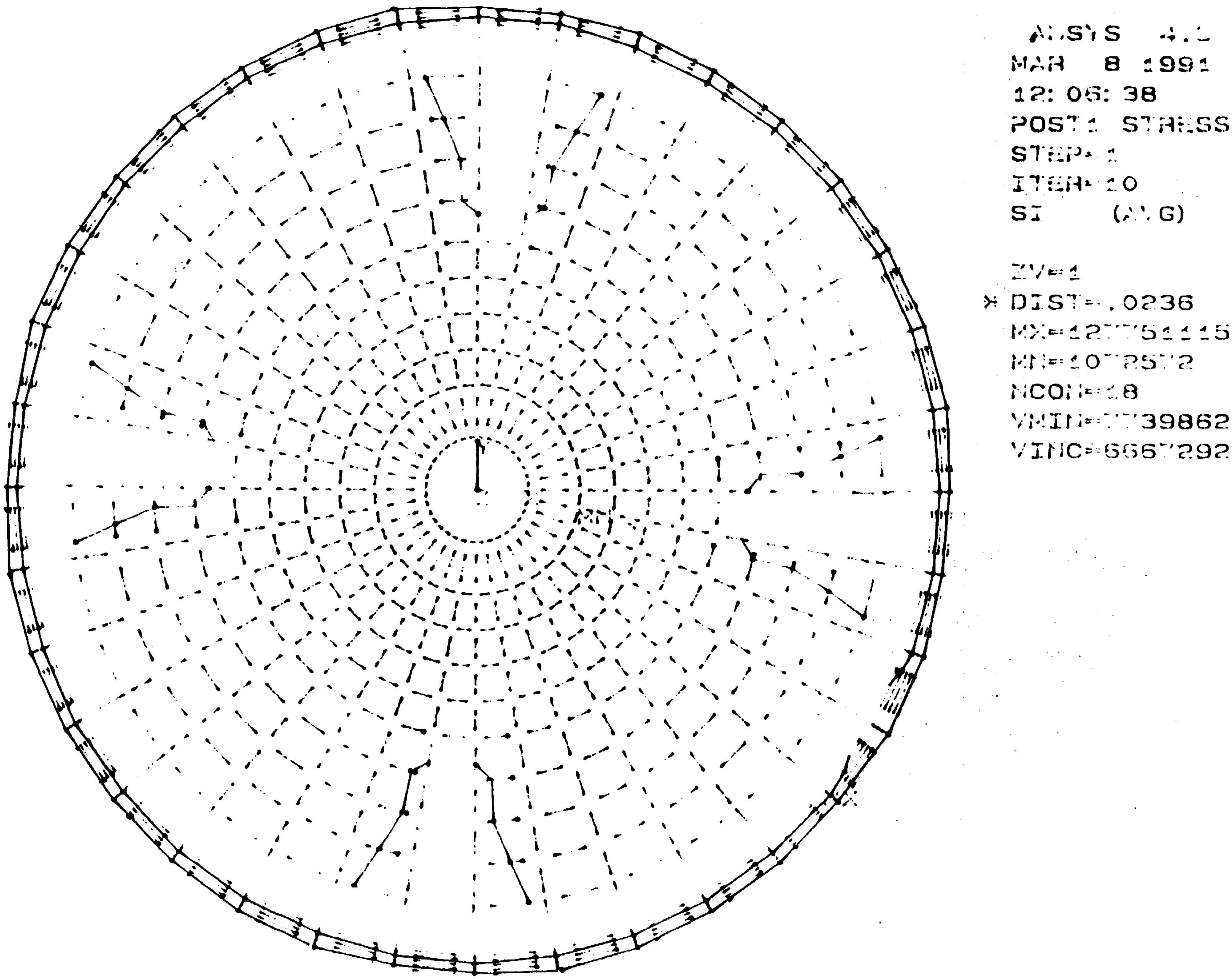
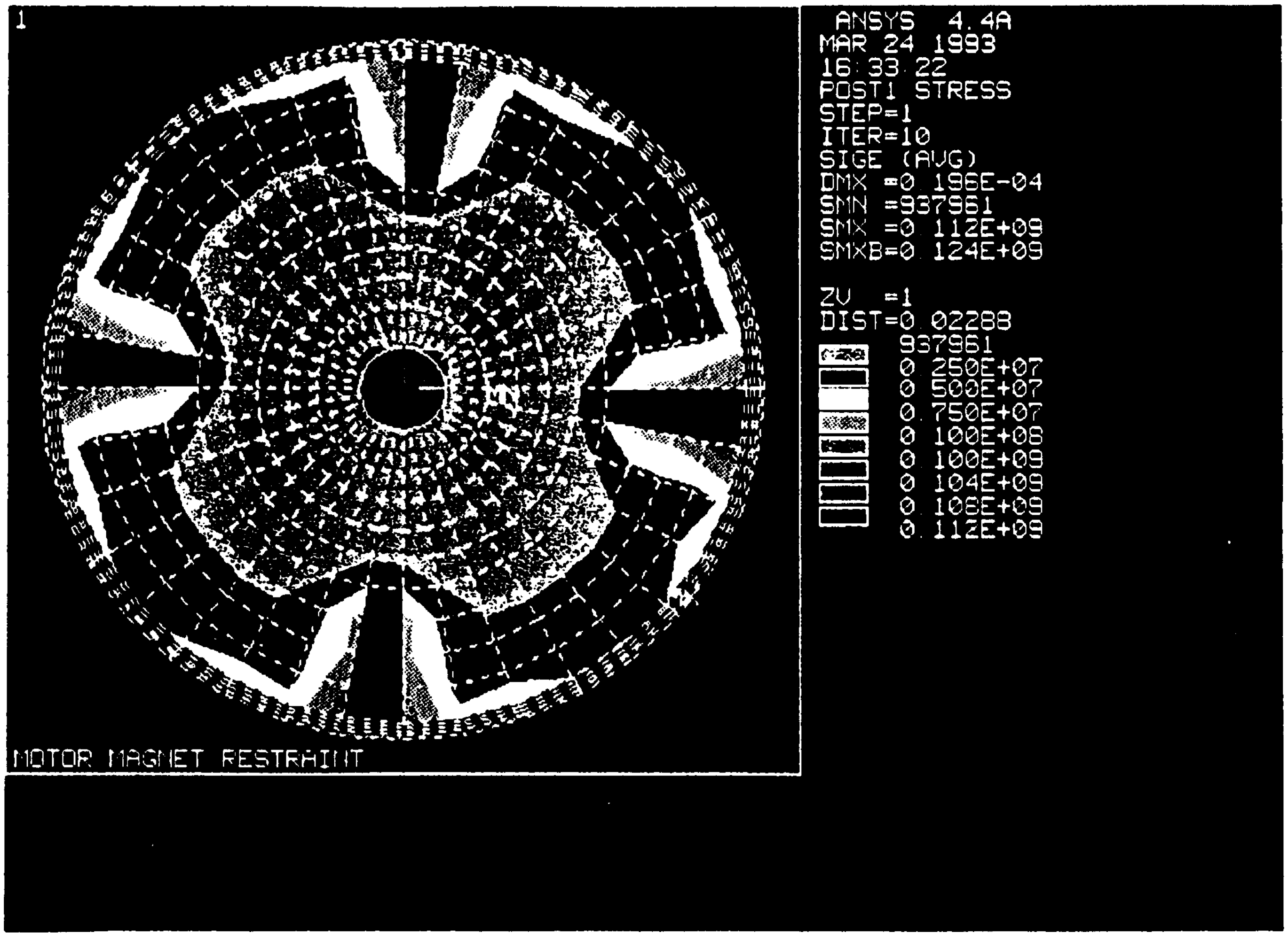
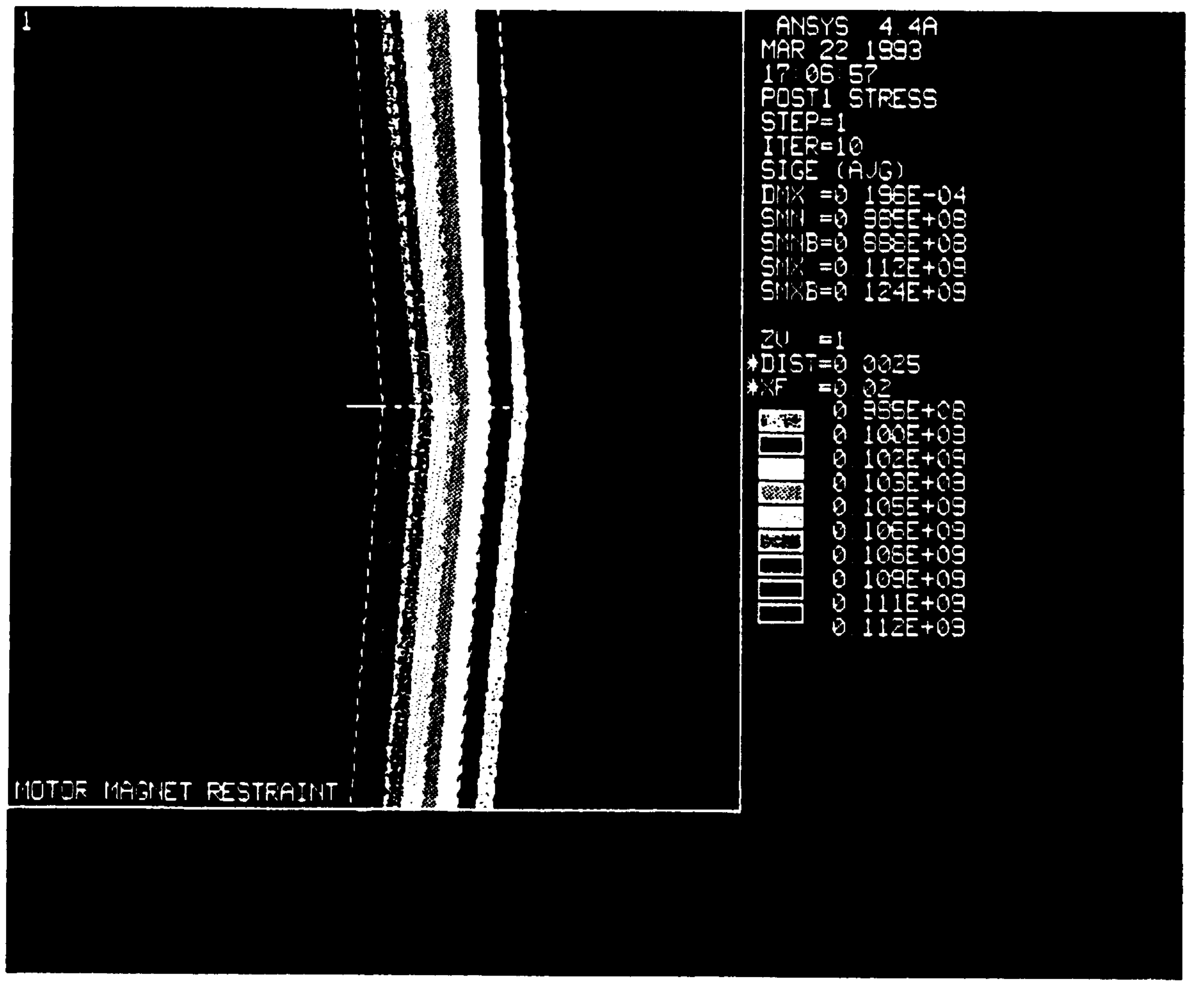


Figure 3.

Rotor Stress Plot



Enlarged View of Stresses In Titanium Sleeve



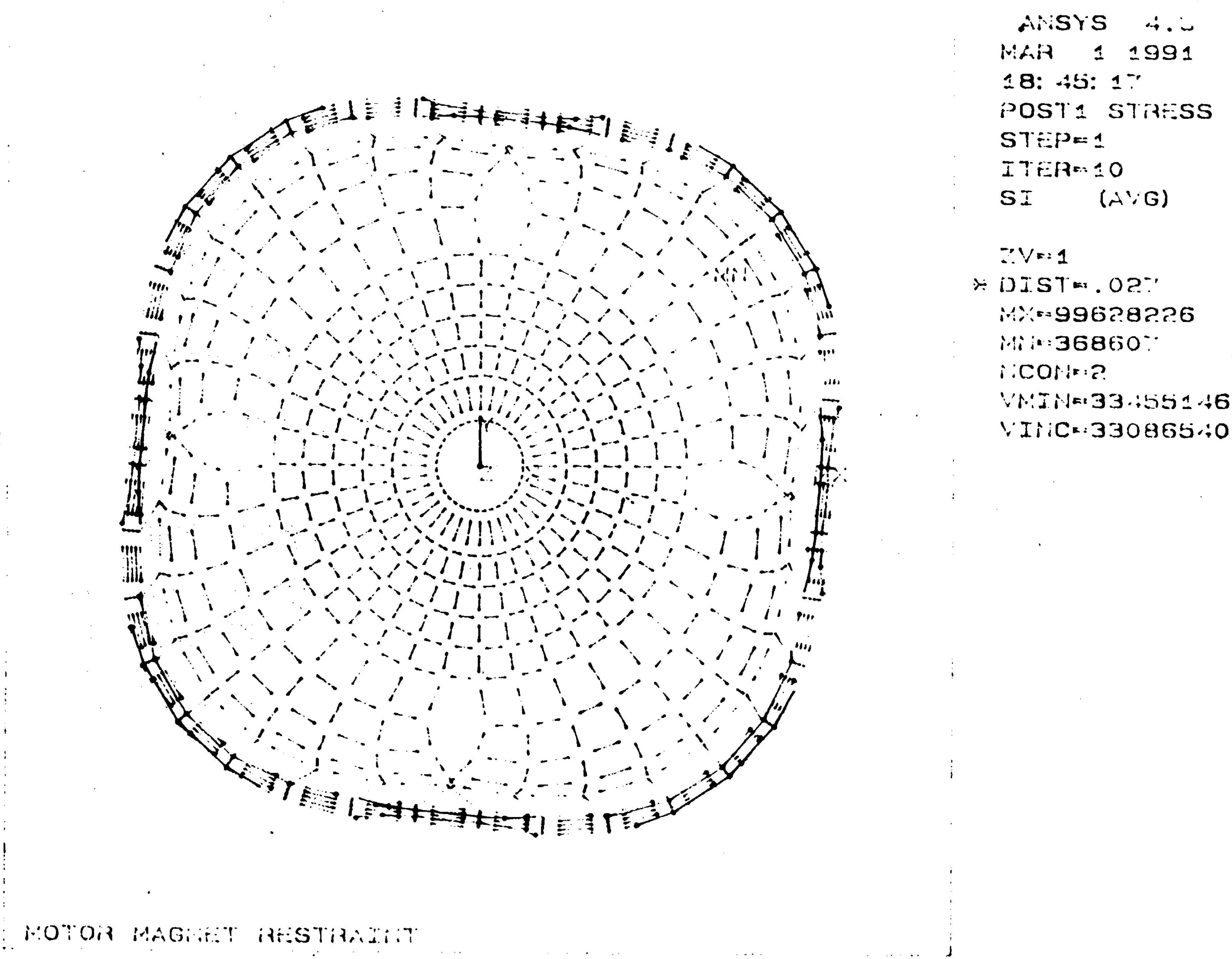

ANSYS 4.3
MAR 1 1991
18: 45: 17
POST1 STRESS
STEP=1
ITER=10
SI (AVG)
ZV=1
DIST=.027
MX=99628226
MN=368607
NCON=2
VMIN=33455146
VINC=33086540
MOTOR MAGNET RESTRAINT

Figure 4.

Appendix A.

Program listing

```
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NUXY,4,[illegible]
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EGEN,35,2,1
E,71,72,2,1
MAT,2
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N,105,.01186,0
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E,[illegible],1002,1007,1006
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[illegible]
[illegible]
[illegible]
[illegible]
```

material properties.

EX = modulus of elasticity

DENS = density

NUXY = Poissons ratio

material 1 = motor shaft

material 2 = rotor

material 3 = magnets

material 4 = retaining sleeve

inner radius of the motor shaft.

radius of the motor shaft

radius from the center of the motor shaft to the outside of the rotor

radius from the center of the motor to the outside of the magnets

same as above plus a very small distan[ce]

radius from the center of the mot[or] to the outside of the restraining sleeve.

amount of radial interference

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OF POOR QUALITY

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0,10,UX
0,55,UX
OMEGA,,,2005
ITER,+10
CNUR,,,1,E-5
WRITE
FINISH
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angular velocity of the motor in radians per second.

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Appendix B.

Nodal stresses at magnet bases

```
***** POST1 NODAL STRESS LISTING *****

LOAD STEP      1   ITERATION=     10   SECTION=  1
TIME=     .00000E+00       LOAD CASE=  1

THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM    1

 NODE     SX            SY            SZ            SXY           SYZ           SXZ           SIG
    SIG2          SIG3          SI            SIGE
  235  -.6214E+07 -.5086E+07 -.3188E+07  .8262E+06 -.1349E-05  .4942E-05 -.30
E+07 -.3555E+07 -.7882E+07  .4831E+07  .4604E+07
  240  -.6210E+07 -.5084E+07 -.3186E+07 -.8232E+06  .3258E-13  .1197E-12 -.30
E+07 -.3553E+07 -.7878E+07  .4829E+07  .4602E+07
  245  -.4694E+07 -.2517E+07 -.2016E+07 -.2422E+06  .3408E-06  .3768E-05 -.20
E+07 -.2440E+07 -.4771E+07  .2755E+07  .2574E+07
  250  -.3256E+07 -.2202E+07 -.1525E+07  .1295E+06  .2661E-06 -.2308E-05 -.15
E+07 -.2129E+07 -.3329E+07  .1804E+07  .1592E+07
  255  -.2691E+07 -.2036E+07 -.1321E+07  .1162E+06 -.1511E-06  .1783E-05 -.13
E+07 -.1980E+07 -.2747E+07  .1426E+07  .1238E+07
  260  -.2553E+07 -.1986E+07 -.1267E+07  4093.        .8751E-09 -.2748E-06 -.12
E+07 -.1957E+07 -.2581E+07  .1314E+07  .1146E+07
  265  -.2685E+07 -.2050E+07 -.1323E+07 -.1135E+06  .0000E+00  .0000E+00 -.13
 07 -.1991E+07 -.2744E+07  .1421E+07  .1233E+07
  270  -.3262E+07 -.2220E+07 -.1532E+07 -.2068E+06  .3106E-06  .2592E-05 -.15
E+07 -.2142E+07 -.3339E+07  .1808E+07  .1594E+07
  275  -.4725E+07 -.2534E+07 -.2029E+07  .2356E+06  .4540E-06 -.5193E-05 -.20
E+07 -.2458E+07 -.4801E+07  .2771E+07  .2588E+07
  280  -.6278E+07 -.5098E+07 -.3209E+07  .8331E+06 -.1423E-05  .5243E-05 -.30
E+07 -.3586E+07 -.7930E+07  .4861E+07  .4629E+07

MAXIMUMS
NODE        280           280           280           280           190           190           2
        280           280           280           280
VALUE    -.6278E+07 -.5098E+07 -.3209E+07  .8331E+06 -.1472E-05  .5397E-05 -.3
9E+07 -.3586E+07 -.7930E+07  .4861E+07  .4629E+07
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
***** POST1 NODAL STRESS LISTING *****

LOAD STEP      1  ITERATION=     10  SECTION=  1
TIME=    .00000E+00     LOAD CASE=  1

THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM    1

 NODE     SX          SY           SZ           SXY          SYZ          SXZ          SIG
    SIG2        SIG3         SI          SIGE
  170  -.2553E+07 -.1976E+07 -.1265E+07  46.75      -.1607E-10  .4429E-06 -.1
E+07 -.1949E+07 -.2581E+07  .1316E+07  .1147E+07
  175  -.2691E+07 -.2033E+07 -.1320E+07 -.1124E+06  .4808E-07  .5863E-06 -.1
E+07 -.1978E+07 -.2746E+07  .1426E+07  .1238E+07
  180  -.3257E+07 -.2201E+07 -.1525E+07 -.1968E+06  .2957E-06  .2602E-05 -.1
E+07 -.2129E+07 -.3329E+07  .1804E+07  .1592E+07
  185  -.4695E+07 -.2518E+07 -.2017E+07  .2447E+06  .4355E-06 -.4767E-05 -.2
E+07 -.2441E+07 -.4772E+07  .2756E+07  .2574E+07
  190  -.6215E+07 -.5089E+07 -.3189E+07  .8254E+06 -.1472E-05  .5397E-05 -.3
E+07 -.3556E+07 -.7885E+07  .4833E+07  .4606E+07
  195  -.6215E+07 -.5089E+07 -.3189E+07 -.8256E+06  .1290E-16  .4729E-16 -.3
 07 -.3557E+07 -.7885E+07  .4833E+07  .4606E+07
  200  -.4695E+07 -.2518E+07 -.2017E+07 -.2448E+06  .4367E-06  .4777E-05 -.2
E+07 -.2441E+07 -.4772E+07  .2756E+07  .2574E+07
  205  -.3257E+07 -.2201E+07 -.1525E+07  .1967E+06  .3502E-06 -.3083E-05 -.1
E+07 -.2129E+07 -.3329E+07  .1804E+07  .1592E+07
  210  -.2691E+07 -.2033E+07 -.1320E+07  .1124E+06 -.1689E-06  .2060E-05 -.1
E+07 -.1978E+07 -.2746E+07  .1426E+07  .1238E+07
  215  -.2553E+07 -.1976E+07 -.1265E+07  59.76      -.2556E-10  .5511E-06 -.1
E+07 -.1948E+07 -.2581E+07  .1316E+07  .1147E+07
  220  -.2691E+07 -.2033E+07 -.1320E+07 -.1123E+06  .3858E-07  .4712E-06 -.1
E+07 -.1977E+07 -.2746E+07  .1426E+07  .1238E+07
  225  -.3256E+07 -.2200E+07 -.1525E+07 -.1965E+06  .2556E-06  .2253E-05 -.1
E+07 -.2129E+07 -.3328E+07  .1804E+07  .1592E+07
  230  -.4694E+07 -.2517E+07 -.2016E+07  .2450E+06  .4721E-06 -.5160E-05 -.2
E+07 -.2440E+07 -.4772E+07  .2755E+07  .2574E+07
```

```
 08 13:08 1991  MOUT.DAT Page 1

PRINT  ALL  NODAL STRESSES PER NODE

    ***** POST1 NODAL STRESS LISTING *****

 LOAD STEP     1  ITERATION=    10  SECTION=  1
 TIME=   .80000E+00      LOAD CASE=  1

 THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM   1

  NODE    SX          SY          SZ          SXY         SYZ         SXZ         SIG
     SIG2        SIG3        SI          SIGE
  105  -.6160E+07 -.5080E+07 -.3171E+07 -.8160E+06  .1416E-05  .5185E-05 -.30
E+07 -.3530E+07 -.7845E+07  .4803E+07  .4586E+07
  110  -.4669E+07 -.2505E+07 -.2006E+07 -.2497E+06  .4265E-06  .4550E-05 -.20
E+07 -.2427E+07 -.4748E+07  .2742E+07  .2561E+07
  115  -.3250E+07 -.2188E+07 -.1519E+07  .1899E+06  .3659E-06 -.3335E-05 -.15
E+07 -.2120E+07 -.3319E+07  .1799E+07  .1580E+07
  120  -.2691E+07 -.2023E+07 -.1317E+07  .1100E+06 -.1653E-06  .2064E-05 -.13
E+07 -.1970E+07 -.2744E+07  .1427E+07  .1239E+07
  125  -.2555E+07 -.1969E+07 -.1263E+07  649.6       .0000E+00  .0000E+00 -.12
 07 -.1943E+07 -.2581E+07  .1318E+07  .1149E+07
  130  -.2692E+07 -.2030E+07 -.1319E+07 -.1107E+06 -.2368E-07 -.2935E-06 -.13
E+07 -.1975E+07 -.2747E+07  .1427E+07  .1239E+07
  135  -.3258E+07 -.2200E+07 -.1525E+07 -.1950E+06  .2537E-06  .2254E-05 -.15
 +07 -.2129E+07 -.3329E+07  .1804E+07  .1592E+07
  140  -.4696E+07 -.2520E+07 -.2017E+07  .2464E+06  .3286E-06 -.3572E-05 -.20
E+07 -.2442E+07 -.4774E+07  .2757E+07  .2575E+07
  145  -.6219E+07 -.5093E+07 -.3191E+07  .8272E+06 -.1164E-05  .4260E-05 -.30
E+07 -.3559E+07 -.7890E+07  .4836E+07  .4608E+07
  150  -.6215E+07 -.5092E+07 -.3190E+07 -.8249E+06  .1144E-18  .4194E-18 -.30
E+07 -.3557E+07 -.7886E+07  .4834E+07  .4607E+07
  155  -.4695E+07 -.2519E+07 -.2017E+07 -.2446E+06  .3994E-06  .4374E-05 -.20
E+07 -.2441E+07 -.4773E+07  .2756E+07  .2574E+07
  160  -.3257E+07 -.2201E+07 -.1525E+07  .1969E+06  .3794E-06 -.3337E-05 -.15
E+07 -.2129E+07 -.3329E+07  .1804E+07  .1592E+07
  165  -.2691E+07 -.2033E+07 -.1320E+07  .1125E+06 -.1464E-06  .1704E-05 -.13
E+07 -.1978E+07 -.2746E+07  .1426E+07  .1238E+07
```

APPENDIX I

Inertia Considerations

Mention has already been made in the main body of the report about inertia concerns. For ready refernece are listed immediately below the results of optimizing the motor, spur gear, roller screw configuration for maximum acceleration.

```
                4 Jm Sqrt[Jrs]
       Sqrt[-------------- + 4 Sqrt[Jp] Sqrt[Jrs] + 8 Jrs] PI
                  Sqrt[Jp]
{{l -> -----------------------------------------------------,
                                 Sqrt[Jl]

            1/4
         Jrs
   n -> ------}, {l ->
           1/4
         Jp
```

The various Js in the formulas represent the various inertis and reflected masses in the system. The spur gear ratio is denoted by n and the roller screw ratio by l. See the original work for all the definitions. These results make it plain that the interrelationships are subtle.

The following material exerpted from the previous report is included to lend some heuristic insight into the foregoing relationships.

It has been stated elsewhere in this report that to obtain maximum possible performance from a motor, gear train and load combination it is necessary to match carefully the motor to the load by careful selection of a gear ratio between the two and then repeat the matching process for a number of differing motors to ascertain the best possible load acceleration performance. The results may be counter intuitive to a casual observer because in many minds it is natural to think in terms of the motor and its speed and acceleration rather than the speed and acceleration of the load. In the present design environment it is possible to select motors of the same rated horsepower with different available torque capacities because of different speeds at which the motors are rated (and they therefore have differing attendant polar mass moments of inertia) as well as being able to select independently the gear ratio(s). Thus in the present case only the load is a fixed quantity - and it is the load in whose motion one is intrerested. The results of this procedure are presented in this report for the multipass gear train case but a simpler example will perhaps help to cement the principles involved.

Consider the case of a motor coupled to a load by a simple one pass gear train. Now examine the accelerations of the motor and the load. The system inertia referred to the motor shaft will be given by

$$Jtm=Jm+Jl/n^2$$

while the system inertia referred to the load is given by

$$Jtl=n^2\ Jm+Jl$$

Where n is a step down gear ratio from the motor to the load and is greater than one in magnitude, Jt denotes a total inertia either at the load (1) or the motor (m), JM is the motor rotor inertia and Jl is the load inertia.

The expression for the motor acceleration is given by

$$accel(m)=T/Jtm=T/(Jm+Jl/n^2)$$

and the load acceleration is

$$accel(1)=T\ n/(Jl+Jm\ n^2)$$

where T is the torque available from the motor.

Inspection of these expressions show immediately that to maximize the acceleration of a given motor n should be made as large as possible; in the limit the motor becomes uncoupled from the load (Jl/n^2 approaches 0). Finding the maximum acceleration of the load is a more tedious matter but if the derivative of the load acceleration is taken with respect to n and the results set to zero the results become

$$n=SquareRoot[Jl.Jm]$$

$$accel(1)max= T/(2\ SquareRoot[Jl\ Jm]).$$

Thus even in the simplest case finding the correct match of inertias through gear train ratio selection is more involved than maximizing the motor acceleration. And in this case for a given load different motors with different maximum torques and different inertias will

produce different maximum load acceleration (which is desired for maximum bandwidth or speed of response). In this maximized load acceleration case the acceleration of the motor will be (by simple substitution) expressed by

$$\text{accel(m)}=T/(2\ Jm)$$

which is certainly lower than could be achieved by a higher gear ratio (as n approaches infinity accel(m) approaches T/Jm).

It is hoped that the simple example discussed above will help the intuitive reasoning process concerning motor and gear ratio selection for a given load. Hopefully it lends insight into why the multipass gear case is somewhat involved to optimize with respect to load acceleration and motor-gear train selection, as has been done in this report.

References

1. Silneader, P. P., and Ferrari, R. L., Finite Elements for Electrical Engineers, Cambridge University Press (Second Edition 1990).

2. Skilling, H. H., Fundamentals of Electric Waves, John Wiley and Sons, (Second Edition 1948).

3. Corcoran, G. F., Basic Electrical Engineering John Wiley and Sons, (1949).

4. Doane, G. B. III, Campbell, W., Brantley, L. W., Dean, G. F., Advanced Electric Motor Technology Flux Mapping, March 1992.

5. Jackson, J. D., Classical Electrodynamics, John Wiley and Sons, (1962).

6. Slemon, G. R., Straughen, A., Electric Machines, Addison-Wesley Publishing Co., (1982).

7. Puchstein, A. F., Lloyd T. C., Conrad, A. G., Alternating Current Machines, John Wiley and Sons, (Third Edition, 1954).

8. Pront, R. E., Rockwell Procurement Specification MC621-0015, 22 November 1982.

9. McAdams, W. H., Heat Transmission, McGraw-Hill Book Company, (1954).

10. Myers, N., Cowan, R., EMTVC Actuator EMTVCZ, MSFC Drawing Number 64EM000 (J size), (8-26-91).

11. Staff and Graduates Advanced Engineering Program, Fundamentals of Engineering Analysis, General Electric Company, (1953).

12. Jokl, A. L., Electric Generators Technology Status, IEEE Aerospace and Electronics Systems, Vol. 6, No. 12, (12-91).

13. Eshbach, O. W.,. Handbook of Engineering Fundamentals, John Wiley and Sons, (1965).

14. ____________, Alloy Data, Carpenter High Permeability "49" Alloy, Carpenter Steel Division, Carpenter Technology Comp., ______________.

15. Pender, H., DelMar, W. A., Electrical Enginers Handbook Electric Power, Fourth Edition, John Wiley and Sons (1949).

16. Liwschitz-Garik, M., and Whipple, C. C., Electric Machinery, Volume II A-C Machines, D. Van Nostrand (1950).

17. Liwschitz-Garik, M., and Wipple, C. C., Alternating-Current Machines, Second Edition, D. Van Nostrand (1961).